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Mass Stabilization as a Ground Improvement Method for Soft Peaty

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Abstract

Construction of road embankments or other infrastructures on soft peat is a challenge. The main problems are high compressibility and rather low undrained shear strength of peat. Mass stabilization provides a solution to improve the properties of a peaty subgrade. Mass stabilization is a ground improvement method, where hardened soil mass is created by adding binder into soil and by controlled in situ mixing. Mass stabilization poses an alternative solution for conventional mass replacement or other techniques, which leave peat in place. The chapter deals with mass stabilization of soft peat soil. Specific attention is paid to design, research and construction considerations, and experience obtained during last three decades. Peat properties before and after stabilization, design methods including pre-testing, stabilization technique and machinery, quality control methods and practices, binder technology, long-term performance of mass stabilized peat, environmental effects, feasibility, applications, and limitations are all presented and discussed in this chapter. The long-term observations (during the last 25 years) have shown that the strength of stabilized peat has continued to increase in average 1.6 times from the strength of 30 days. Therefore, mass stabilization has proven to be a flexible ground improvement method for peat layers with maximum thickness of 8 m.

Keywords: peat, soil properties, mass stabilization, deep mixing, ground improvement, design, execution, long-term performance

1. Introduction

Design and construction of road embankments on soft, compressible, peaty and organic soils is a demanding task for the geotechnical engineer. The primary challenges include the high

compressibility of the peat deposit together with very low undrained shear strength [1, 2]. Traditionally, there are three common solutions for foundation engineering in peat areas:

- 1. Total removal of peat and replacement with imported, inorganic aggregate fill.
- 2. Leaving peat in place and using soil improvement methods.
- 3. Transfer load through the peat layer via piles or columns to lower, load-bearing soil layers.

A visual concept of the various methods available is presented in **Table 1**. Improvement method (a), mass replacement of the peat units with inorganic, compacted fill material, is not treated in detail in this document. Methods that leave the peat in place, presented as method (b) in **Table 1**, can be generally divided into four groups of techniques in which the peat layer is used as a load-bearing layer. Those techniques are (1) pre-compression, (2) reinforcement, (3) load modification, and (4) deep stabilization (deep mixing). Piling, which is presented as method (c) in **Table 1**, is not considered a peat treatment methodology because the entire embankment load is transferred to underlying bearing units, and thus no load is applied to the untreated or treated peat.

(a) Mass replacement	Excavation and replacement
	Mass exchange by squeezing
	Deep compaction
(b) Pre-compression	Preloading
	Surcharging
	Staged construction
Reinforcement	Synthetic georeinforcements
	Geocell mattress
	Timber grillage
Load modification	Lightweight fill (LWA, EPS, ...)
	Counter berm
	Profile lowering
Deep stabilization (deep mixing)	For the whole peat layer (Figure 1a)
	To a given depth (Figure 1b)
	Combination of mass and column stabilization (Figure 1c)
(c) Piles	Piles and concrete slab (concrete or steel piles)
	Pile caps and georeinforcement (concrete or steel piles)
	Wooden piles and georeinforcement
Columns	Stone columns

(a) Peat replacement techniques, (b) peat left in place techniques, and (c) embankment load on supporting piles or columns.

Table 1. Ground improvement technologies at peat areas.

Deep stabilization (deep mixing) methodologies encompass a number of methods applied to stabilize peat masses in situ. Of these, the mass stabilization method is one of the commonly applied methods. Mass stabilization is taken to mean a ground improvement method in which added binder is mechanically mixed into the soil mass to harden and improve its engineering characteristics. The mass stabilization method presented in this paper was invented in Finland in the early 1990s and subsequently has been utilized in more than 30 countries. Mass stabilization reduces settlement, improves bearing capacity and stability, and supports slopes and excavations in soft soils. To achieve all of these targets in diverse applications, a significant amount of academic and industrial research, knowledge, and experience concerning stabilization of peat has been analyzed and subsequent collected into manuals and various other publications. Most completed stabilization projects have been successful; however, some negative outcomes have also been observed. Case studies of failures have been highly instructive also and have demonstrated the limitations of the method and highlighted areas requiring additional development.

Mass stabilization may be applied to a broad range of geotechnical engineering projects, including roads (illustrated in **Figure 1**), streets, railroads, municipal engineering, harbors,

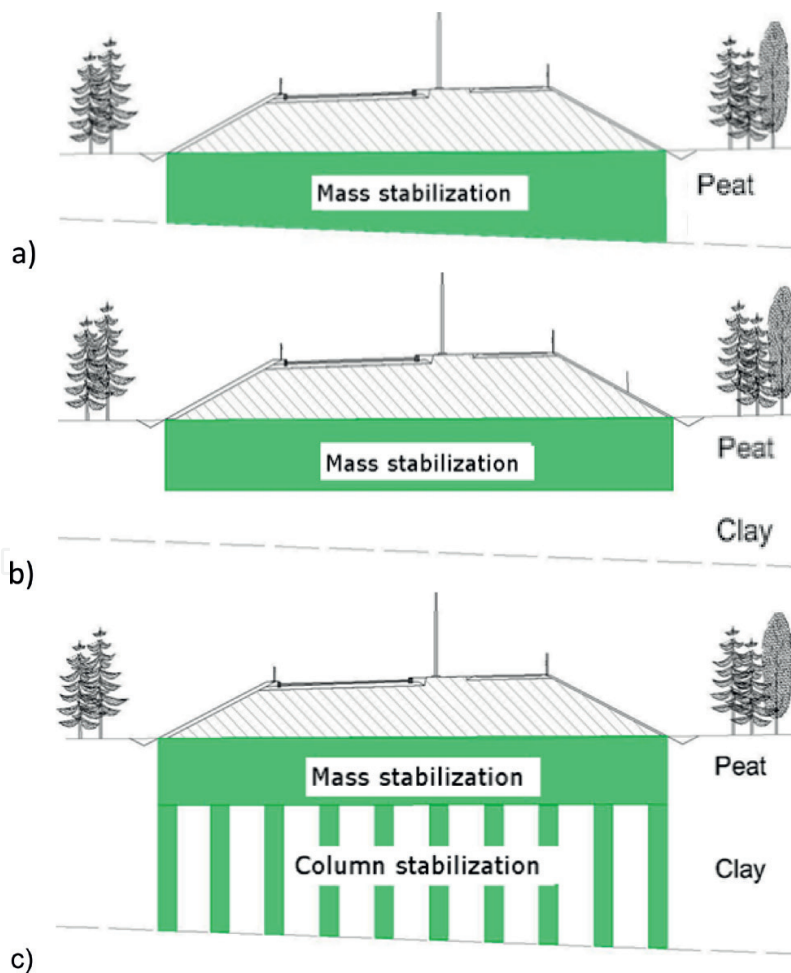


Figure 1. Mass stabilization (a) in lower level of soft soil layer, (b) mass stabilization to a designed target depth, and (c) combination of mass stabilization and column stabilization [3].

landscaping sites, flood protection, industrial sites, and commercial areas. Simple machinery (excavator with mixing tool, binder feeder, binder tank) and fast production rate allows for cost-effective application in comparison with traditional methodology. Additionally, environmental considerations favor the use of mass stabilization, because in situ techniques diminish the need to excavate and transport the peat, thus reducing carbon emissions from the peat deposit. The in situ technique binds the embedded carbon dioxide within the peat unit and reduces the production of methane and nitrous oxides. While the technique allows to keep drainage at high level (peat is not drying), the carbon dioxide equivalent release will stay low. The laboratory tests of Duggan et al. with stabilized peat indicate that stabilized peat not only holds its carbon but also the binder used seemed to uptake CO_2 both from the atmosphere and the peat [4]. These carbon emission reduction factors are expected to be significantly greater than the CO_2 emissions associated with the production of binder materials.

The intent of this chapter is to promote and encourage the use of mass stabilization techniques to improve peaty soils by highlighting project experiences and positive outcomes observed over several decades. These experiences have developed confidence in this cost-efficient and environmentally friendly method.

2. Engineering properties of peat

2.1. Classification of peats

Peat consists of organic material in various degrees of decomposition; it may contain residual vegetation or be wholly decomposed and amorphous. Peatlands occur throughout the world in environments in which vegetation does not fully decay, because the conditions are acidic or anaerobic. The partly decayed material accumulates and retains water, creating peatland areas [5]. Finland has the highest proportional area of peatlands (33.5%) in the world [6], which measured mean peat thickness of 1.4 m [7]. The deepest peatlands are situated in Southern Finland, where peatlands have typical depth of 4–6 m [8].

Von Post developed a classification system for peats in 1922, based on the degree of decomposition and including 10 separate categories [9]. In recent years, simpler classification systems, which refer on the structure of the peat, have been created by Radforth [10] and Landva [11]. These systems are generally considered to be more useful in geotechnical engineering, because they related mechanical properties to the structure. The recent European Standard SFS-EN ISO 14688-1 specifies that peat deposits can be classified based on the degree of decomposition. The classification test is comparatively crude, utilizing a visual-manual classification via a hand squeezing test. Peat is classified into three categories in SFS-EN ISO 14688-1 standard [12]: (1) fibrous, (2) pseudo-fibrous, and (3) amorphous.

Stratigraphically, peat layers are most often the uppermost soil layer [5]. Fibrous peat forms the uppermost layer, and the peat mass typically transitions toward the completely amorphous phase in the lowest part of deposit [2, 13]. The measured pH value for Finnish peats varies between 3.7 and 5.8, for example [13, 14].

2.2. Sampling and testing

Peat presents a challenge for testing because it is difficult to obtain representative, undisturbed samples for testing. Often larger samples are used and testing methods are adapted to accept the larger specimen size; examples of modified test protocols include the Rowe cell test [15] for oedometer (settlement) testing and large shear box test [13] for shear strength evaluation. Traditional difficulties in sampling and testing explain the comparatively limited engineering data available for peats. Additionally, peat units are heterogeneous due to their history and evolution and known variation in structure as noted above; as a result, peat layers typically exhibit clear and significant anisotropy. For example, Helenelund [16] reported that compression strength is approximately equal in the vertical and horizontal direction, but the tensile strength was clearly larger (nearly five times) for horizontal direction. Additionally, Ahonen [15] reported for fibrous Veittoistensuo intact peat samples that tested in horizontal friction angle was 17° and vertical 20° degree. The corresponding cohesion values were 7 and 0 kPa, respectively, for Veittostensuo fibrous peat. Fibrous peat also exhibits some degree of tensile strength.

2.3. Water content

Peat water content is typically high and varies considerably; common water content values of Finnish peat vary between 500 and 2000%. Typically, fibrous peats have higher water content than amorphous peats [1, 2]. In Finnish peats, the observed values for Leteensuo peat [13] varied between 300 and 1000% for pseudo-fibrous and 400–650% for amorphous peat. Ronkainen [17] reports that the mean water content for Finnish peats is 710% and median 673% ($N = 172$). Consistency limits (Atterberg limits) can be defined for amorphous peat, but not for fibrous [17].

2.4. Density

The in situ bulk density of natural peats varies depending on its water content. For amorphous peat, bulk density can be up to 1200 kg/m^3 , while for an unsaturated fibrous peat including wood debris, density may be as low as 600 kg/m^3 . The density is higher if inorganic minerals are present. The specific density is typically between 1.5 and 1.8 kN/m^3 [2]. According to Ronkainen [17], the unit weight of mean and median is 10.3 kN/m^3 ($N = 159$).

2.5. Permeability

The permeability of peat depends on its morphology and may vary significantly. The permeability of an unloaded peat lies typically between 10^{-4} and 10^{-7} m/s [17]. When peat is loaded and has compressed, its permeability decreases. Carlsten [18] reported values around 10^{-8} m/s for compression degree of 60%, and Munro [19] reported values as low as 10^{-11} m/s . Deformation properties of natural peat are a very important consideration because the primary consolidation of peat is significant and permeability changes rapidly with consolidation. The secondary compression of peats is essentially linear and progresses indefinitely, but in any case rate of compression decreases over time and will reach an end state at an indeterminate point after loading [20]. Jelusic [21] observed in laboratory conditions that approximately 90% of primary compression occurred during first 1–2 hours, with measured vertical

compressive strain of approximately 60% under 80 kPa vertical load. Carlsten [5] observed a connection between water content, loading level, and deformation. Van den Haan and Kruse [22] cited the isotache model (originally developed by Leroueil et al. [23]) as a reliable method to evaluate settlements including both primary and secondary phases. The isotache model depends on the OCR and density of the peat.

2.6. Influence of mineral content

In addition to the influence of water content and degree of decomposition, measured strength parameters depend also on the mineral content of the peat. In general, increasing water content and degree of decomposition tend to reduce the strength characteristics of a peat, while increasing inorganic mineral content has the opposite effect and tends to lead toward increased strength [24].

2.7. Undrained shear strength

The undrained shear strength of normally consolidated fibrous peat may range between 6 and 7 kPa [19]. Forsman [25] reported that in Letteensuo-swamp the undrained shear strengths defined with vane test have varied between 5 and 30 kPa, with majority of results occurring between 10 and 15 kPa. In peat material, the strength is not usually increasing as a function of depth as is common for clays, because self-weight is so small. It is possible that the strength is actually decreasing in deeper layers, where the more amorphous peats are laying [19, 26].

3. The effect of mass stabilization on peat properties

The goal of the mass stabilization is to improve the geotechnical engineering performance of a soft subgrade (e.g. peat) by using an admixed binder agent. Mass stabilization significantly alters the geotechnical characteristics of soils and particularly peats. The target shear strength in mass stabilization generally varies between 40 and 70 kPa, being rarely more than 100 kPa. Many factors, such as peat properties, binder recipe (type and quantity), curing time, temperature, preloading level, and time, affect the result of the mass stabilization process and its rate of change. Mass stabilization changes the index properties of peat (i.e., water content, bulk density, pH, etc.), its strength and deformation properties, and water permeability [3]. **Figure 2** illustrates the effect of mass stabilization on the unconfined compressive strength and deformation.

Veittostensuo-swamp is located in South-Eastern Finland, and its characteristics are generally considered to be broadly reflective of typical Finnish peats. Veittostensuo was the first mass stabilized peat area, which was studied carefully, and therefore a significant body of research exists. These studies have informed the development of the mass stabilization process, binders, and quantities. The following paragraphs present selected results from the Veittostensuo peat stabilization studies.

The data obtained from Veittostensuo test studies include several laboratory test series, for example [15, 28], to develop binder material, addition rate, and results of field tests series, for example [24]. The strength in the field was defined using various sounding methods; more

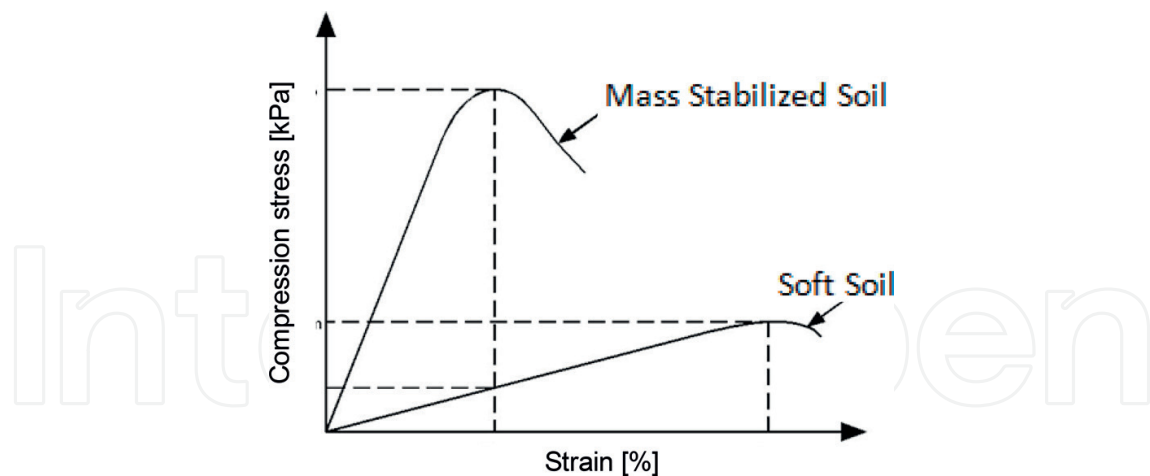


Figure 2. The impact of mass stabilization on strength and stiffness of soft soil [27].

details are presented in Section 8 and by Piispanen [24]. The thickness of peat varied between 2.2 and 3.5 m, with the fibrous upper part comprising the upper 1.2–2.4 m thick layer [28].

3.1. Initial neutralizing effects

Stabilization proceeds such that the binder agent first neutralizes the soil, and thereafter, additional binder introduced creates the desired stabilization effects. Janz and Johansson [29] and Babasaki et al. [30] have suggested that there is a minimum threshold value for binder agent, after which the strengthening reactions start. It is understood that initial addition of an alkaline binder first neutralizes the soil, and only after this buffering process can binding begin. In previous Veittostensuo case studies, the amount of binder utilized has clearly exceeded the minimum threshold value and the stabilization has succeeded.

3.2. Long-term pH trends

During stabilization of the soil units, the pH value of stabilized peat increased from the mean initial value of 4.6–12.5 during the first year. The long-term pH values have decreased to an average pH of 11.5 [24]. The value after the first year is still clearly high enough to demonstrate that the hardening is permanent. The reason for decrease in pH is thought to be the result of inflowing water from the non-stabilized part of the swamp and corresponding increase of water content. This conclusion is supported by observed decrease in water content during the stabilization process and subsequent increase in time elapsed after stabilization. In this case, the measured water content of peat decreased from original values of 1170–1670% (note that the amorphous peat had higher values) to approximately 170% after 1 year and subsequently increasing to average value 270% after a period of 23 years [24]. While the peat is assumed to be fully saturated, the increase was thought to mean that the peat is swelling and taking in additional water. Settlement monitoring has revealed, however, that settlement continued from first year to 23 years, and measured strength has increased, thus implying that no swelling has occurred. Therefore, it is considered more likely that during the stabilization process the water content has decreased sufficiently that the soil is only partly saturated because at least some of the pore water has been bound to the dry solid binder during the stabilization chemical

Property	(a) Intact peat	(b) Age 1 day to 1 year	(c) Age 1–23 years
pH	4.5–4.7 [33]	(1) 12.5–12.8(2) 12.2–13.2 [24]	(1) 11.3–12.2(2) 11.7–12.3 [24]
W (w-%)	1170–1470 [15]	(1) 160–210(2) 110–190 [24](1) 170–200(2) 100–190 [34]	(1) 230–370(2) 200–260 [24]
Unit weight (kN/m ³)	7.9–16.3 [33]	10.4–15 [31](1) 11.3–12.3(2) 10.9–2.7 [34]	–
Specific weight (t/m ³) [33]	1.66–1.69	–	–
Void ratio, e (–) [15]	18.3–22.2	–	–
Permeability, k (m/s) [24]	10 ^{–5}	10 ^{–6} –10 ^{–8}	–
Compression index C _c (–) stress level 40–80 kPa [15]	7.5–9.3	0.11–0.13*	–
Efficient cohesion c' (CIDC, kPa, strain 15%)	1–6 [15]	(1) 30–512(2) 54–100 [15](1) 46–84(2) 37–49 [34]	–
Effective friction angle φ' (CIDC, °, strain 15%)	19–20 [15]	(1) 21–22(2) 22–35 [15](1) 29–30(2) 37–41 [34]	–
Undrained shear strength (kPa)	7–20(vane test) [28]	(1) 50–100(2) 70–150 (vane test) [31]	(1) 70–100(2) 50–150 (vane test) [33]
Elastic modulus E _d (CIDC, kPa), strain 1.5%	1000–1900 [15]*	(1) 5100–8000(2) 7200–12,200 [15](1) 1700–7900 [34]	–
Bulk modulus K _d (CIDC, kPa) [15]	–	(1) 8000–11,500(2) 9500–17,800	–
Poisson's ratio ν'	0.36–0.4 [33]	(1) 0.1–0.21(2) 0.1–0.20 [15]	–
Compression modulus, M [15] stress level 40–80 kPa (kPa)	100*	(1) 4300(2) 4000	–
Coefficient of consolidation, c _v stress level 10–80 kPa (m ² /a)	0.9–19.3 [15]	(1) 640–3300 (Taylor) [15]	–
Coefficient of creep, C _a stress level 40–80 kPa	0.44–0.55 [15] oedometer	0.013field [24]	0.037field [24]
Thermal conductivity (W/mK)	0.39 [32]	0.20–0.57 [32]	–

*The presented values are the minimum and maximum values of laboratory tests for fibrous, amorphous intact peat and stabilized peat.

(1) Binder mixture of Finnstabi (including gypsum) and rapid cement 50% + 50%, 250 kg/m³.

(2) Binder mixture of rapid cement and blast furnace slag 50% + 50%, 300 kg/m³.

Table 2. The literature values of properties of non-stabilized (a) and stabilized (b, c) peat including references (Veittos-tensuo, Finland).

reaction. The dry mixing process also adds some air to the soil via the use of compressed air injected in to the mass [31]. In any event, observations of the peat units over the long term indicate that the saturation degree of the stabilized peat increases slowly over the long term.

3.3. Binders

Ahonen [15] used two different binders in his preliminary laboratory tests: (1) a mixture of Finnstabi® (including gypsum) and rapid cement mixed in the ratio of 50%/50%, addition rate of 250 kg/m³ and (2) mixture of rapid cement and blast furnace slag mixed in the ratio of 50%/50%, addition rate of 300 kg/m³. These same binders and amounts were chosen for the execution. The target shear strength for the peat was 50 kPa [28].

3.4. Deformation and strength properties

Ahonen [15] performed the oedometer test with Rowe cell ($\phi = 254$ mm). The tests were started right after stabilization, and it was observed that in the beginning peat compressed 12–17% with the first loading step of 5 kPa. When the binding process started, the settlements practically ended, starting only after the loading exceeded 80–160 kPa, resembling the behavior of clays with pre-consolidation pressure. For intact peat, it is impossible and useless to define pre-consolidation pressure, because primary consolidation starts immediately after application of load. The deformation parameters decreased such that, for example, the compression index for stabilized peat was less than 10 times smaller than that of intact peat. The consolidation rate (coefficient of consolidation) on the other hand increased significantly [15]. Additionally, it is important to observe that post-stabilization creep rate was effectively zero.

Mass stabilization brought remarkable increase in both effective and undrained strength values [24, 31] although not as significant as were the increase in deformation properties [31].

The field studies of Huttunen et al. [32] utilizing a thermal needle probe showed that thermal conductivity of the stabilized peat after 1 year varied between 0.20 and 0.57 W/mK, and the average was nearly the same as for intact peat 0.39 W/mK. This result means that stabilized peat, like intact peat, forms a thermal insulation.

In situ saturation degree of stabilized soil varies over long period, depending on the water absorption capacity and the permeability of the stabilized soil [31]. Incomplete saturation produces matrix suction, which leads to an increase in the undrained strength.

Table 2 presents observed geotechnical properties of peat in Veittostensuo case also as a function of time. The presented values are the minimum and maximum values of laboratory tests for fibrous, amorphous intact peat and stabilized peat. Estimated values have been defined from the test result diagrams; therefore, they are not exact values, rather giving a magnitude of the property. The mass stabilization mixed the peat layers therefore the values of fibrous or amorphous peat has not been specified in **Table 2**.

4. Mass stabilization applications and technique

4.1. Applications

Mass stabilization can be used in versatile applications as a ground improvement method and as a processing method for low-quality soils. Applications include [3]:

- roads, streets, and railways;
- municipal engineering;
- harbors and sea routes (fairways);
- landscaping sites (e.g. parks);
- environmental protection structures;
- industrial and commercial areas;
- housing construction areas; and
- flood protection.

Mass stabilization can be executed in the following ways [3]:

- Full penetration depth through the whole thickness of soft soil layers (**Figure 1a**).
- Partial penetration to a given depth (i.e. a “floating” structure, **Figure 1b**).
- Optimized as a combination structure—mass stabilization on top of column stabilization (**Figure 1c**)

In full depth mass stabilization, an almost non-settling ground improvement result can be achieved. In the case of partial mass stabilization to a given design depth, compressible soil layers are left under the stabilized zone. In this case, settlements will occur, yet the load induced by the embankment is distributed via mass stabilized layer to the lower layers, thus evening out the settlements and reducing differential settlements. The stress caused by the new structures affects the magnitude of these settlements. Settlements may be significant, if the applied stresses exceed the pre-consolidation stress of the lower soil layers.

Column stabilization carried out under mass stabilization reduces the settlements of the soft soil layers underneath mass stabilization. Additionally, this method improves the stability of the embankment by impeding the formation of a slip surface. Most commonly, the combination of mass and column stabilization is used in cases when peat or mud constitutes the uppermost soil layer, because the column stabilization method alone would not provide sufficiently strong columns for the upper part. Mass stabilization can also be used as a working platform for stabilization machinery in the areas with particularly weak subgrade conditions.

4.2. Technique

The principle of the mass stabilization method is presented in **Figure 3** and field photographs of mass stabilization implementation in **Figure 4b**. With the current equipment, the mixing tool attached to an excavator allows the execution of stabilization to depth of 7–8 m under favorable conditions. The optimal stabilization depth is typically in the range of approximately 3–5 m. However, thinner layers can also be mass stabilized. Commonly used mixing tools are presented in **Figure 4a**.

In the “Nordic stabilization method,” mass stabilization is carried out by using the dry technique, i.e. addition of dry binder or binder mixture. Wet mixing technique (alt. “slurry”), in which the binder is premixed with water before pumping and mixing to soil layer, can be used as well. It is noted in any case that the “wet method” requires an alternative type and design of feeder than the “dry method” and additionally demands significantly higher binder addition rate. This article deals only with mass stabilization with dry method.

The soft soil layer is commonly mixed to “pre-homogenize” the unit prior to injection of the binder. This process is intended to create a uniform pre-stabilization soil mass and thus a predictable and consistent result. A pressure feeder injects the binding agent (one or two binders, or a binder mixture) through the hose of the mixing tool. The rotating drums mix the binding agent into the ground and homogenize simultaneously the mixed mass. Mixing is executed by moving the mixer unit vertically and laterally from the surface to the desired depth. The reach of an excavator determines the progress of stabilization work. The work area is commonly divided into blocks, or areas, of equal size depending on the site geometry. Typically, the size of a block is between 3 and 5 m² and the work proceeds from block to block. The working capacity of a mass stabilization system depends on the soil material, but in general it varies between 50 and 200 m³ of stabilized soil per hour and per mass stabilization unit [3].

To account for and counteract the natural loosening of the soil mass produced by mixing and air injection, a preloading embankment of 0.5–1 m height is constructed above the stabilized soil to promote hardening of the mass stabilized soil beneath the ground surface. The preloading embankment can be raised in stages after some hardening has happened to achieve a target final design level. However, regardless of site leveling objectives, experience indicates that the preloading embankment is indispensable to ensure the consolidation of the stabilized material during the hardening process (cf. curing of cement). The target strength of the mass stabilization is typically achieved in a period of 1–3 months [3].

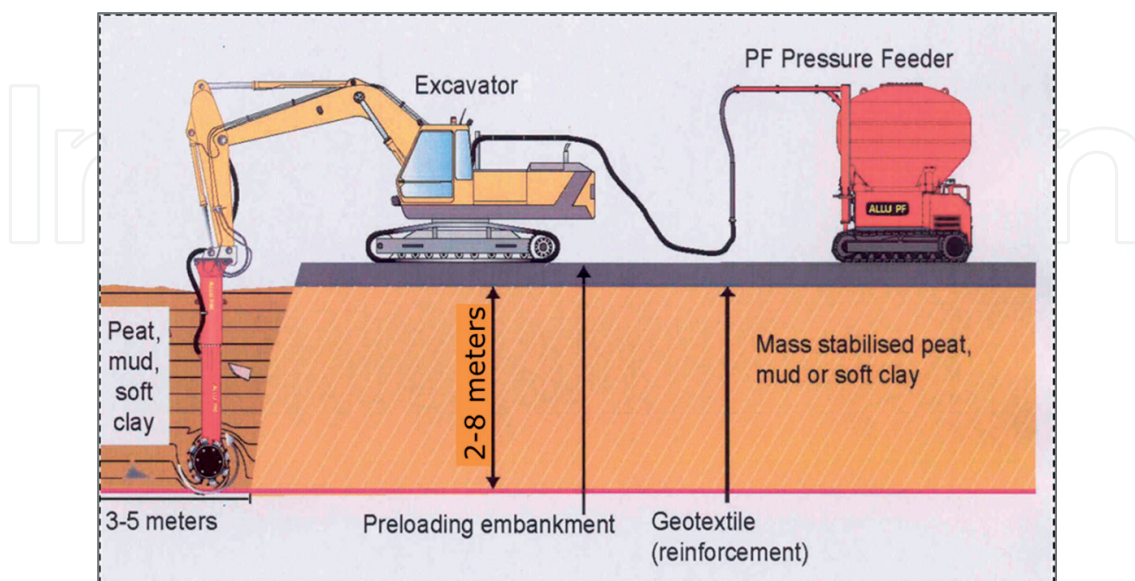


Figure 3. Mass stabilization equipment. Elements, such as a mixing unit, pressure feeder, and the control and data collecting unit, are attached to the excavator ([35], modified).

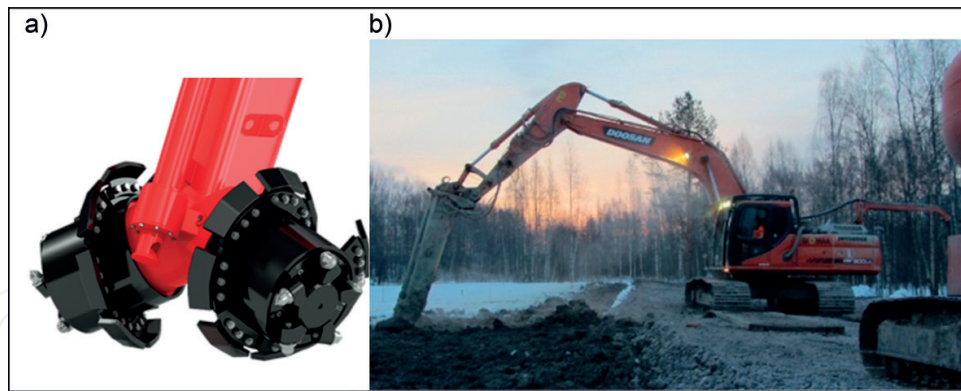


Figure 4. Mass stabilization mixing tool (a) [36]. Mass stabilization work ongoing at temperature -12°C (b) [photo Heikki Hämäläinen].

5. Mass stabilization binders

5.1. Binders

All mass stabilization projects utilize a binder, or chemical stabilizing agent, that reacts with the peat mass to change its strength and deformation properties. During the mixing and curing process, other soil properties, such as water content, degree of saturation, and permeability, are also altered [33]. As a result of the ground investigation and laboratory testing programmes, the quantity and quality of the binder are optimized to achieve target properties with minimal investment.

The chemical reactions involved in the hydration of different types of cement or lime and processes involved in soil stabilization using a variety of binders have been described and discussed thoroughly, for example in the thesis of Åhnberg [31]. The reactions generated when mixing various binders with soil vary by process, intensity, and duration, but in general, exhibit many similar characteristics. Hydration process will start after the binder is mixed in to the soil. Fly ash and slag can need a binder activator. Åhnberg indicates that some reactions may involve directly starting cementation. Some other may lead to further reactions with the soil and its minerals [31].

Up to approximately 70% of the unit price of mass stabilization can be dependent on the price of binder. Cement is the most commonly used binder in mass stabilization. Alternative solutions like industrial by-products are favored since cement is relatively expensive and it has considerably high carbon footprint [27]. The replacement of cement with binders based on industrial by-products (e.g. fly ash, oil shale ash, furnace slag powder, and gypsum) in the stabilization of peat has been studied widely both in the laboratory and in the field. The aim of using industrial by-products is to produce a positive impact on the technical and environmental quality of the stabilized masses, as well as to diminish the cost of the binder mixture. The environmental acceptability is evaluated by testing leaching of contaminants from the stabilized material in the laboratory. The results of the tests provide good reasons for the use of fly ash-based binders in the mass stabilization of peat [3, 37].

There are some general guidelines for the correct binder solution to a given peat stabilization project, based on laboratory tests and field stabilization. In the guidebook EuroSoilStab

[38] cement, cement+gypsum or cement + furnace slag are presented as generally suitable for stabilization of Nordic peat units. Additionally, cement + oil shale ash has proven to be a very effective binder mixture for Baltic peat [24]. Huttunen and Kujala observed in their feasibility study that fibrous peat is easier to stabilize than amorphous and that the parent plant type significantly influences the stabilization process [34]. Later, more comprehensive research has indicated that peat is a complex material and these arguments may be oversimplified.

In general, it is possible to mix the treated peat layer with various subcomponents such as additional aggregate materials, for example, sand or clay, in addition to the binder materials. Prior to the actual stabilization, these components are spread on the harrowed peat surface to be premixed with excavator to peat layer and mass stabilized. These components are then admixed into the soil either during pre-homogenization or mixing. That procedure improves the final result of mass stabilization [3].

In Finland, an environmental permit is needed for the use of by-product or waste material-based binders such as fly ash in mass stabilization, in the event that the product is not commonly utilized as a binder product and CE-marked or otherwise authorized for this use by a regulatory authority. Waste materials carry a high disposal tax (70 €/t as of 1.1.2016 in Finland) in the event that they are not utilized; as such, the producers of these types of waste materials are motivated to offer their material as stabilization binder [27].

In response to industry demand, in 2006, the Finnish Ministry of the Environment has prepared the "Government Decree on the recovery of certain waste in earth construction." The objective of this decree is to promote the recovery of waste by specifying conditions, which, if complied with, mean that the use of waste referred to in this decree in earth construction will not require an environmental permit in accordance with the Environmental Protection Act (527/2014). A new version of this decree is expected to become valid 2018, and more materials and applications (like use as a stabilization binder) are included in the new version [39].

5.2. Stabilization tests

Stabilization laboratory tests are used to define the technically and financially most competitive options, of which is then chosen the most suitable solution for the site in question [38, 40]. Sometimes, for example with contaminated soils, environmental qualification properties also affect the choice. The objective of the research is to ascertain the quality properties of the final product and to select the most applicable binder and the optimal binder amount.

The determination of the material properties to be achieved through stabilization process is carried out with sufficient accuracy to allow development of reliable geotechnical dimensioning (stability and settlement) and plans. For the needs of the design, it is important to know material variations in the area of concern and their impact on the results of stabilization and the speed of strength development [3].

After mixing binder into the peat in the laboratory, the stabilized mass in the cylinders is preloaded with a vertical load (usually 18 kPa). Under the loading, the stabilized peat compresses substantially over the curing period, particularly during the early stages of curing. The mass compacts and water exits from it due to the compression. The effect of preloading on the achieved

strength is significant. Based on previous experiences, the achieved strength of preloaded specimens has a much better equivalence to the stabilization strengths measured in actual site conditions, as opposed to the strength of specimens when preloading has not been applied [3]. The tests also give approximate knowledge concerning the anticipated magnitude of compression of the stabilized peat layer. By varying the magnitude of the preload used in the laboratory tests, it is also possible to estimate the effect that a possible preloading embankment could have on the strength development or settlement behavior of the stabilized peat. The properties to be defined from the laboratory-made hardened specimens shall at the very least include the compressive strength and Young's modulus E (E_{50}) from unconfined compression tests [3, 40].

In demanding sites, it is recommended that the strength parameters and deformation properties of the stabilized soil should be determined using triaxial shear tests. The triaxial test enables better imitation of the prevailing load conditions and deformations taking place in the ground than the unconfined compression test [3, 40].

The strength of a laboratory-made stabilized test sample is usually higher than the strength of a corresponding material from the field, and thus a correction factor may be applied. This factor $\tau_{\text{field}}/\tau_{\text{laboratory}}$ is based on experience, and if there is no earlier experience, it can be necessary to perform test stabilization.

At present, there are no EN standards for the stabilization tests, but some national guidelines exist (e.g. in Finland [40] and in Sweden [41]), and in addition, an unofficial European guideline for stabilization in EuroSoilStab guidebook has been published [38].

6. Stages of project and execution

6.1. Project

The main stages of a mass stabilization project are as follows [3, 38, 42]:

- collecting initial information and data;
- feasibility study;
- initial site investigations and design including initial stabilization tests in laboratory;
- dimensioning and actual stabilization tests in laboratory;
- design, technical drawings, work specifications, quality assurance plan;
- competitive bidding;
- stabilization works and quality control; and
- follow-up quality control and reporting

The first, preliminary evaluation of the applicability of mass stabilization as a soil improvement solution at a given site can normally be done with comparatively incomplete initial data, assuming there exist previous experiences of deep stabilization from the area in question [3, 40].

The more unfamiliar the ground conditions are, the more initial data are needed for even the preliminary technical and economical evaluation. The important part of the “feasibility study” is to find out whether the site is suitable for mass stabilization work. In this phase, the following issues need to be investigated [3]:

- rocky fill layers, previous failures, etc.
- hard soil layers in the zone to be stabilized,
- pipelines, underground cables, etc.,
- existing structures (e.g. piles, timber grillage, etc.),
- climate condition (flood, drought, frost, etc.),
- accessibility of the site (roads for transportation of machinery and binders), and
- geographical location (distances, interest of contractors).

Geotechnical design and analysis sets the target strength for the mass stabilized layer, and the binder recipe is developed in order to comply with the strength requirements. In the case of “demanding” soils, where it is challenging to achieve satisfactory hardening of the stabilized layer, the target strength is established on the level which can be obtained with the use of a reasonable binder amount (e.g. the target that may be achieved with a reasonable price per cubic meter of mass stabilized soil). The design calculations commonly carried out in the process of designing a mass stabilized structure include stability and settlement calculations. In stability calculations, the mass stabilized layer is assumed to be an elastoplastic soil layer and the uncertainties of the results of the homogenization must be taken into consideration. The settlement of a mass stabilized layer has to be calculated at least in two phases—during hardening under the compaction embankment and after hardening under the final embankment [3].

6.2. Execution

Mass stabilization is executed according to plans, which might be updated and/or complemented during the progress of work. Mass stabilization projects require creation of a target-specific work organization plan, which describes how the work should be carried out in practice and how the contractor should demonstrate the obligatory quality assurance and quality control tasks. Stabilization work can be roughly divided into the following stages in the procedure where the mass stabilization equipment is working on the compaction embankment [3]:

1. Topsoil removal.
2. Removal of objects that disturb stabilization works and leveling of the area.
3. Marking of stabilization areas and blocks.
4. Ground level measurements.
5. Stabilization work (=mixing binders with sub soil).
6. Construction of compaction embankment.

7. Quality control of the stabilized layer.
8. Quality control and follow-up of the stabilized area.

In some cases, the procedure is altered, and the working platform is constructed straight against cleared subsoil and the stabilization machine is working over platform mixing the platform material to the subsoil before adding and mixing of the binder agent.

The following preliminary works are required to be done at the area to be stabilized: harrowing and clearing of trees, bushes, stubs, and roots and removal of fills, structures, or materials that would make the stabilization works either difficult or impossible to execute. The drainage of the area has also to be arranged in the cases where there is open water over subsoil [3].

The location of the stabilization grid is set out before the launch of stabilization. Before the production of the actual stabilization takes place, it is possible to execute a trial area. Trial stabilization makes it possible to check the designed binder and binder amount so that the required design strength can be reached. Usually, the actual production stabilization is started directly after the trial phase is done. Since every stabilization project is unique, stabilization work always needs to be designed on a case-by-case basis [3, 40].

During the binder feeding and mixing, the stabilized soil layer becomes loosened. The compacting embankment is normally constructed over blocks after binder injection and mixing to ensure compaction and consolidation of the stabilized layer and to enable the excavator to move on into the site (**Figures 3 and 4b**). This also allows for a faster start of reactions in binder and the removal of surplus air and water from the mass stabilized structure. In cases, when column stabilization is made under peat layer before mass stabilization of the peat layer (**Figure 1c**), the working platform is constructed straight against harrowed subsoil surface before column and mass stabilization. After column stabilization, the platform material is mixed to subsoil during or before binder injection and mixing and, after mixing, a primary compaction embankment has been constructed over blocks. The thickness of the primary compaction embankment is normally 0.5–1 m [3].

The following standpoints relating to the equipment and the construction site should be considered while the stabilization work is underway [3, 40]:

- weather conditions/temperature;
- the room reserved for the equipment at the site;
- changes in the ground conditions;
- how the binder(s) will be delivered and stored at the site; and
- preliminary curing of the layer to be stabilized how it affects the progression of the work.

Executing the stabilization in winter conditions is possible, but very harsh cold delays the curing process. In Finland, mass stabilization has been carried out even in the really low temperatures of -20 to -30 °C, but this is generally not recommended. If the ground is frozen, it

might be necessary to use a drop hammer to enable excavation works. This will reduce work efficiency and make the hardening time longer.

6.3. Quality control QC/QA

Mass stabilization design documentation sets objectives and requirements for binder, stabilization work, and the final structure. The contractor keeps a record of fulfilling the objectives and requirements concerning stabilization work. The quality of stabilized layer is compared to the requirements set by the design [3, 35, 39]. 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 setup plan of the site is founded on work specifications that can be complemented by the contractor concerning, for example their own QC actions [3, 42–44].

Quality control done by the contractor happens alongside the mass stabilization work. Usually, this includes monitoring the quality of the soil that is being stabilized, for example the water content, observation of the site conditions 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, and ensuring the homogeneity and compression strength of the final product. Early results of QC allow the remaining stabilization works to be adjusted to fulfill the design objectives. The QA program 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 [3, 43, 44].

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 them are presented in **Table 3**. 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 approximately 10 representative soundings (e.g. column penetrometer) should be performed and at least three vane shear tests should be carried out from a given subarea (**Figure 5**). 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.), and in a larger project, there can be dozens of subareas. Statistical methods should be implemented for evaluation of soil parameters from individual tests (**Figure 6**) [43].

7. Settlements

Settlements within the mass stabilized layer occur in four stages [3, 40, 45] (the phases of mass stabilization settlement are presented in **Figure 7** and an example settlement of Case Veittostensuo in **Figure 8**):

QA methods	Method description	Area and type of the tip
Column penetrometer	Static/dynamic penetration	$A = 100 \text{ cm}^2$, $\phi = 375 \text{ mm}$ (wings)
Vane penetrometer	Vane rotation	$\phi = 130 \text{ or } 160 \text{ mm}$, $H = 0.5 \times \phi$
Combined static-dynamic penetration test	Static/dynamic penetration with rotation	$A = 50 \text{ cm}^2$ for stab. soil
CPT sounding	Static penetration	$\phi \approx 36 \text{ mm}$, $A = 10 \text{ cm}^2$

Table 3. Verification techniques for determination the quality of mass stabilized soil (modified based on [43]).

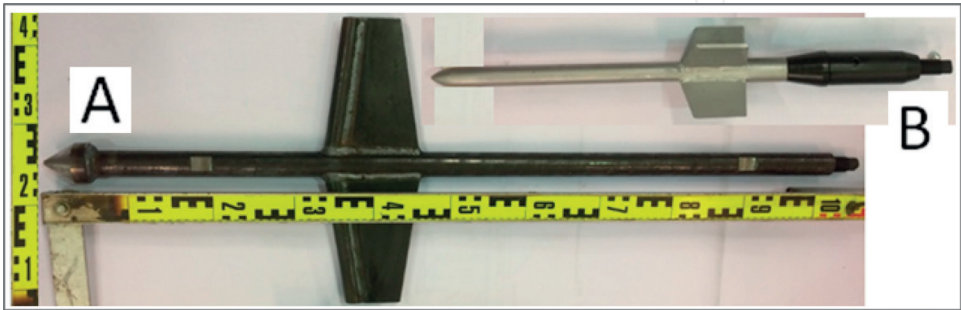


Figure 5. Column (A) and vane penetrometer (B) for columns [40]. The dimensions of the tip A are presented in the standard EN14679 [42] and in mass stabilization handbook [3] and of tip B in handbook.

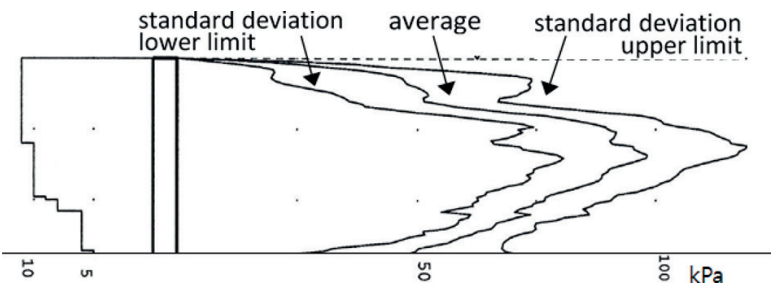


Figure 6. Principle of column penetrometer results from mass stabilized soil layer ($z \approx 2.5 \text{ m}$). On the left is the quantity of the soundings and on the right is presented average shear strength and standard deviation [43].

1. During stabilization work: Dry binder is supplied into the ground with the help of compressed air. It is mixed with the soil using a rotating mixing tool. This often causes some “loosening” of the stabilized soil and causes some raising of the stabilized layer surface.
2. Under the compaction embankment: The largest settlement in a mass stabilized layer happens during the initial compaction of the compaction embankment. A typical compaction embankment height is from 0.5 to 1 m. The embankment is left on place during the curing time to act as a load to the structure.
3. Under the final embankment: The actual embankment is constructed over the compaction embankment. The compaction embankment material can be replaced if considered necessary. Settlement plates are suggested to be used to check the progress of the compaction of the mass stabilized layer before the final embankment is put in place.



Figure 7. Phases of settlement in mass stabilized layer and settlement time diagram [45].

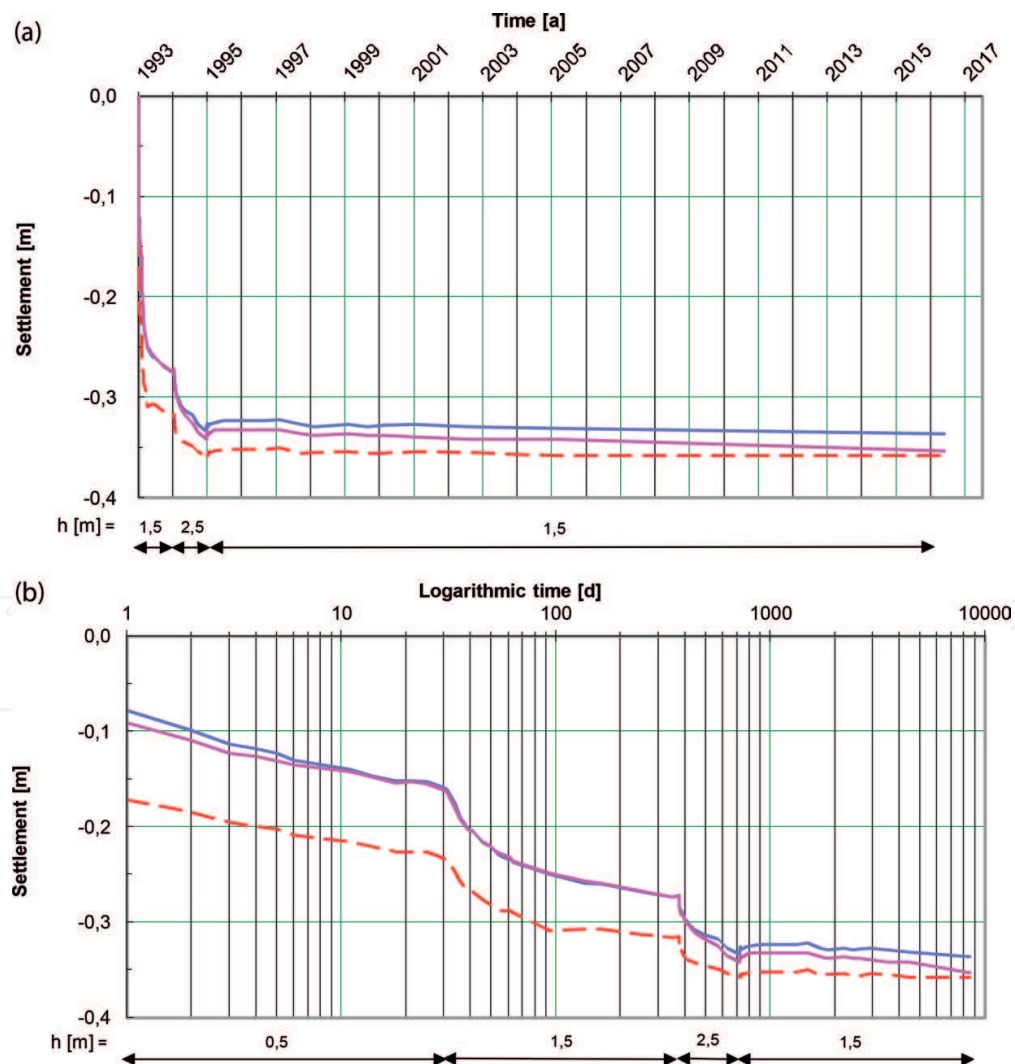


Figure 8. Case Veittostensuo, Finland. Measured settlement of embankment over mass and column stabilized soil (mass stabilized peat and column stabilized clay layer). The thickness of the embankment “h” is presented under the figure. At the horizontal axis, the time in linear (a) and logarithmic (b) scale [24] is presented.

4. Under the preloading embankment: Preloading embankment can be used to create a load equal to the final embankment load or an additional load (surcharge, overloading) on top of the stabilized soil. This is usually the case when settlements happening during the operating life of the structure should be as small as possible. If there are non-stabilized settling layers left under the mass stabilized layer, their settlement must be minimized with preloading or the long-term settlements will continue. When peat is the soil being stabilized, it is usually necessary to use a preloading embankment.

8. Long-term behavior of mass stabilized peat

Behavior of mass stabilized peat in the long term is a point of great importance. From the engineering perspective, long-term behavior consists of settlements, stability, and bearing capacity of the mass stabilized peat layer. The main property affecting these properties is the long-term development of the strength of the layer. No negative behavior should be observed if the design strength is exceeded during the whole lifespan of the mass stabilized peat layer [24].

The strengthening of the mass stabilized soil is mainly based on reaction product bonds between soil particles. Strength commonly increases in time as long as there are reactions taking place in the mass stabilized layer. The rate of the reactions and their associated strength increase are dependent on the binder and treated subgrade type. Åhnberg [31] proposed that hydraulic binders (e.g. cement) tend to have faster strength increase in the short term than pozzolanic binders (e.g. lime). It was also found that pozzolanic binders have better long-term strength increase, which lead to approximately same strength increase between hydraulic and pozzolanic binders within 1 year from the mass stabilization.

Janz and Johansson [29] proposed that the reaction products can break down rather quickly in certain environments. Peat mass stabilization is often exposed to chemical and physical attacks, such as frost damage, lime leaching, and sulfate attack (delayed ettringite formation). Especially when the “Nordic stabilization method” technique is used, the binder amount and achieved strength are relatively low compared to, for example column stabilization. This theoretically exposes mass stabilized peat layer to a greater risk of strength reduction in the long term.

Piispanen [24] has studied the long-term behavior of 6.5–23 years old Finnish and Estonian mass stabilized peat layers using in situ testing. The study focused on defining the development of strength, index properties (e.g. water content, pH), and settlements from the moment of stabilization to the present time.

Piispanen’s study [24] considered that a total of 18 stabilized sections were studied, each differing according to binder or subgrade type and properties. Investigations were completed primarily performing in situ soundings and sampling. New soundings were compared to the previous quality control soundings, which had commonly been performed 30 days from the mass stabilization (measured strength/30-day strength ratio). Mass stabilization depths were divided into 0.5 m depth ranges for assessment. Mean and dispersion values were calculated at every depth interval and the values of similar depth intervals were compared at different times to evaluate the long-term strength increase. The results of the study are presented in **Figure 9** and **Table 4**.

There are settlement measuring results from mass stabilization cases, but the long period settlement measuring data is not as extensive. In the case of Veittostensuo, there are settlement observations from a period of 23 years. These measured results are presented in **Figure 8**. Settlement parameters are determined on the basis of the results presented in **Table 2**. The majority of the settlement has taken place during 2–3 months under the compaction embankment and final embankment. After the surcharge with preloading embankment, the settlement has been minor [24].

In the case of Veittostensuo, water content and pH of the mass stabilized layer were analyzed from the samples taken and compared to the previous results, if possible (**Table 2**). It was noticed that the water content had almost doubled from the samples taken after 1 year from the mass stabilization compared to the samples taken after 23 years. Additionally, the pH value had decreased approximately one unit on a same time range, but remained high (>11). Regardless of these results, the strength of the mass stabilized material had increased throughout the mass stabilized peat [24].

The study [24] concluded that the long-term behavior of peat mass stabilization is from an engineering perspective positive and controlled as the strength of the mass stabilized peat commonly increases in time, and the material tends to be robust for changes of the index properties.

9. Cases

During the past decades, mass stabilization method has become popular as a ground improvement method and as a way of handling soft excavated or dredged soils in Nordic countries, in European countries, in the Far East, Australia, as well as in North and South America. Mass stabilization has been used as an in situ ground improvement method in versatile applica-

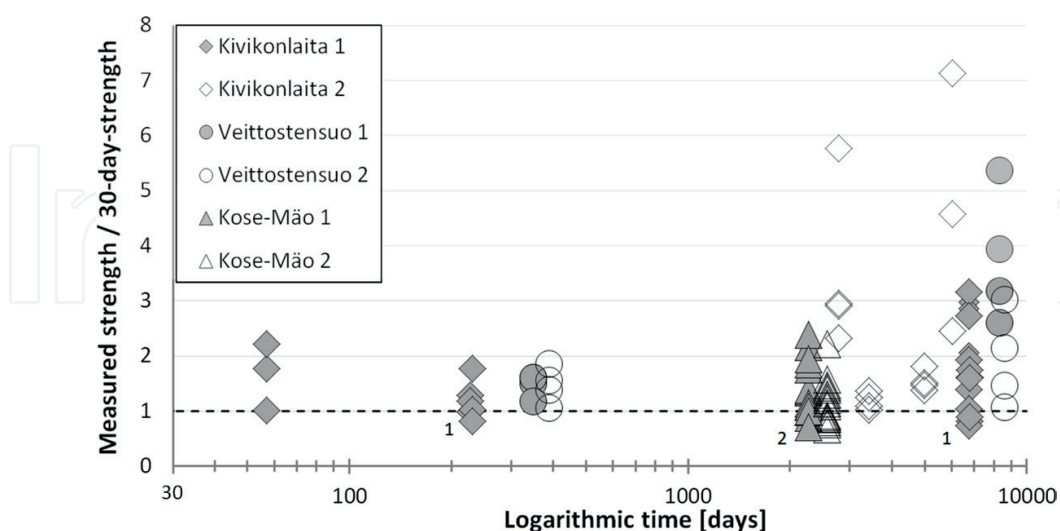


Figure 9. In situ strength development results of mass stabilized peat. Measured strength/30-day strength ratio is presented on vertical axis and time on horizontal axis. Every marker represents that ratio of the same 0.5 m depth range of the mass stabilization at different sounding times. Number A after the site name represents pozzolanic or gypsum (filled marker) and B hydraulic-based binders (empty marker) [24]. (A) Some of the 30 day abnormally high results indicated to an error in measurement and (B) the actual comparison value was 2 months after the mass stabilization and before that the strength increase had been exceptionally strong which indicated that most of the reaction products had already formed.

Site and number of areas	Binder type and amount [kg/m ³]	Age [year]	Sounding type and number	Sample size N*	Strength increase ratio [-]**	COV***
Kivikonlaita 1, Finland (3)	Ce + F[70–113 + 70–113]	18.5	CPT 60VP 9	101127	1.71.7	0.60–1.170.14–0.30
Kivikonlaita 2, Finland (3)	Ce + sand[100 + 150]	9.5–16.5	CP 10CPT 12SDPT 20	401729762	1.23.41.5	0.24–0.300.79–1.070.43–0.79
Veittostensuo 1, Finland (1)	RCe + F[125 + 125]	23	CP 6VP 6	10924	3.82.6	0.17–0.230.44–0.84
Veittostensuo 2, Finland (1)	RCe + BFS[150 + 150]	23	CP 6VP 6	28824	1.92.3	0.39–0.620.40–0.62
Kose-Mäo 1, Estonia (4)	Ce + OSA[70–100 + 100–200]	6.5	CP 24	418	1.4	0.19–0.52
Kose-Mäo 2, Estonia (4)	Ce[150–250]	6.5	CP 24VP 3	58111	1.11.7	0.02–0.450.18–0.55

*Number of collected readings of soundings.

**Strength increase compared to 30-day strength.

***Variation of COV values calculated to 0.5 m depth ranges of mass stabilized layer.

Ce = cement (Portland); F = Finnstabi (lime, gypsum); RCe = rapid cement (Portland); BFS = blast furnace slag; OSA = oil shale ash; sand = extra aggregate; CPT = cone penetration test, tip 10 cm²; PK = column penetrometer, tip 100 cm²; SDPT = static-dynamic penetration test, tip 50 cm².

Table 4. Sites of peat stabilization. Binder type and amount, hardening time of the peat, sounding types and the number of the sounding points, sample size, strength increase ratio and variation of COV [24].

tions for construction at soft soil areas in 25–30 countries [3, 27, 44, 46, 47]. Good experience obtained in those sites has led to expanded application possibilities for this method. Since 1996, mass stabilization has also been applied for processing soft, and in many cases, polluted dredged sediment allowing for their further utilization as material in port development construction works. The largest reported case of this kind is the Vuosaari Port in Helsinki, Finland, at which the amount of mass stabilized TBT-contaminated dredged soft sediment was 0.5 million m³ [48].

In most cases, mass stabilization method has been used for stabilization of soft and watery silt, clay, and mud soils. Mass stabilization of peat is also popular. An example list of cases is presented in **Table 5**, in which mass stabilization of peat has been executed. Two of those cases, Kivikko and Veittostensuo, are presented in greater detail below.

9.1. Case Kivikko

Approximately 10 hectares of the lots and streets in Kivikko, Vantaa, Finland are situated on soft swamp, which required stabilization to ready the subgrade for construction activities. The mass stabilization method was applied in Kivikko for the first time in 1998, and the latest stabilization work was completed by December 2010 [46].

Location and time of mass stabilization execution	Volume [m ³]	Application	Reference
Veittostensuo, Iitti, Finland, 1993	≈1000	Road, test area	[24, 49–51]
Väg 601, Råneå, Sweden, 1995	10,000	Road	[50, 52]
Skyttorp-Örebro, Sweden, 1996	≈15,000	Railroad	[50]
Väg 590, Askersund, Sweden, 1996	7300	Road	[50]
Tolsa, Kirkkonummi, Finland, 1996	≈1000	Road, test area	[53]
Kivikko, Helsinki, Finland, 1997–2010	270,000	Industrial area	[46, 54–57]
Väg 272, Holmsveden, Sweden, 1997	≈20,000	Road	[50]
Väg 45, Arvidsjaur, Sweden, 1998	11,000	Road	[50]
Enånger, Sweden, 1998	≈1000	Test area	[50]
Lielahiti, Tampere, Finland, 2002	≈5000	Street	[57, 58]
Väg 44, Uddevalla, Sweden, 2002	32,000	Road	[59]
IKEA, Vantaa, Finland, 2002–2003	65,000	Yards and street	[60, 61]
Railroad, Mäntsälä, Finland, ≈2004	≈50,000	Piling platform	[58]
Peräseinäjoki, Finland, 2005	≈6000	Railroad	[35, 62]
Edenderry, Ireland, 2005	< 1000	Road, test area	[63]
Key Largo, Florida, USA, ≈2009	n × 100,000	Road widening	[36]
Toukoranta, Helsinki, Finland, 2005–2006	69,000	Park	[46]
Haaga, Helsinki, Finland, 2006	78,000	Sports park and residential area	[46, 57]
Kose-Mäo, Estonia, 2009	≈10,000	Road, test area	[27, 64]
Pitkäjärventie, Espoo, Fin., 2012	85,000	Street, pipeline	*
Nikuviken, Porvoo, Finland, 2012	17,000	Pipeline	*
Simuna, Estonia, 2012	11,000	Road	[27, 65]
Omenatarha, Porvoo, Finland, 2011	≈10,000	Street, pipeline	*
Mellunkylä, Helsinki, Finland, 2011	50,000	Street and residential area	[46]
Roslagsbanan, Täljö, Sweden, 2013–2014	n × 10,000	Railroad	[66]
Turvesuo, Espoo, Finland, 2016	30,000	Yards	*
Honkasuo, Helsinki, Finland, 2016	25,000	Street	*

*Information is from the design documents of the cases.

Table 5. Some examples of mass stabilization cases where intact soil is peat.

Over years, the stabilized area has gradually been expanded. At the beginning of this project, two separate mass and column stabilization development projects were carried out—EuroSoilStab (ESS) and Deep Stabilization Development (DSP). Both took place in the street line at the southern part of the area. In the ESS project, the mass stabilized layer was placed over a clay layer which

was column stabilized to the depth of 7 m. The DSP project was the first attempt to perform column stabilization through the mass stabilized layer. After the development projects, mass stabilization was completed at the yard areas [67]. The stabilized areas are presented in **Figure 10**.

The treated soil material included soft peat (water content 400–1000%) and clay. The top layer was 2–3 m thick peat layer and beneath that was a soft layer of clay. The clay layer reached 3–18 m deep until a moraine layer. The combination of column stabilization and mass stabilization was used under the street and pipelines and mass stabilization (**Figure 11**) or column stabilization solely at the yards of industrial buildings. In the cases of thick clay layers, column stabilization was also performed under the yard areas [24, 67].

The binding agent mixtures in the ESS project were three different combinations of gypsum- and lime-based Finnstabi® 70–113 kg/m³ and cement 70–113 kg/m³. In the DSP project, the used binder agents were cement (100 kg/m³) and a mixture of cement 100 kg/m³ and fine sand 150 kg/m³. The binding agent in the subsequent mass stabilizations was the similar mixture of cement and sand than in the DSP project. By adding sand, it was possible to decrease the amount of binder needed. Depending on circumstances, in 1 day, 800–1000 m³ was mass stabilized by one mass stabilization unit [67].

The designed target shear strength for most of the mass stabilized yard areas was 40 kPa and the quality of the mass stabilization was assured by in situ soundings. The target shear strength value was exceeded [67]. The quality control soundings were repeated in four areas (*Fin: alue*) (“ESS,” “1 ha -alue,” “Urakka-alue 4,” and “Alue C”) in 2017, after 9.5–18.5 years from the

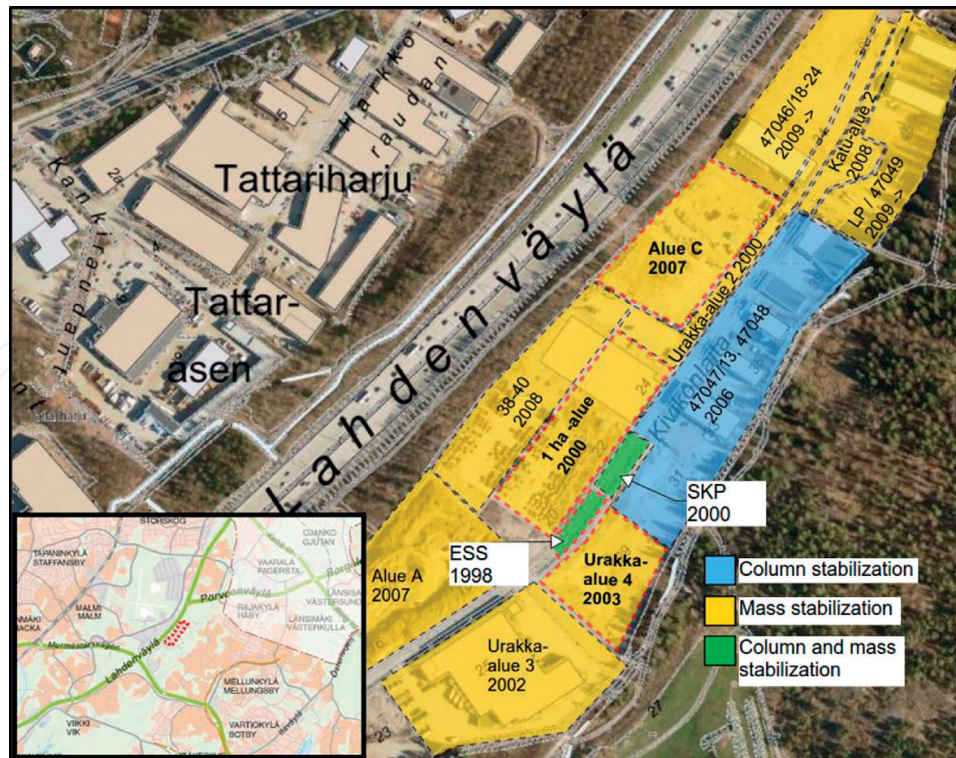


Figure 10. An overview of the locations of the stabilized areas in the industrial area of Kivikko in Helsinki. The length of the area in northeast-southwest direction is 600 and 200 m in opposite direction [24].

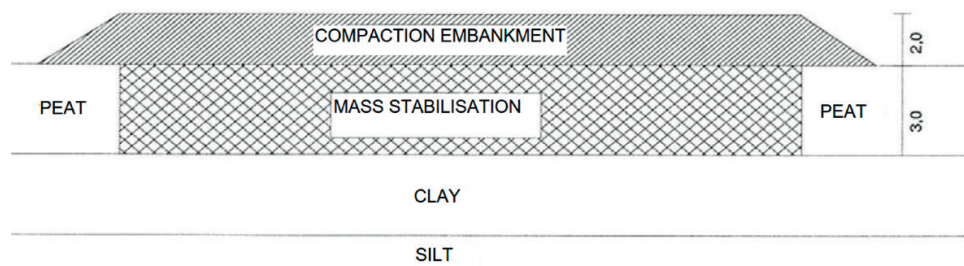


Figure 11. The principle cross section of the peat mass stabilization in the case Kivikko ([67], modified).

stabilization executions. It was concluded that the strength of the mass stabilized material had increased substantially during the observed period of time (**Figure 9** and **Table 4**) [24].

The main objective for the stabilization of the peat layer in Kivikko was to improve the bearing capacity and stability and reduce settlements in a cost-effective way. Another objective was to develop and gather knowledge from the stabilization methods. Both of the objectives were fulfilled.

9.2. Case Veittostensuo

A column and mass stabilized trial embankment was constructed on a swamp in Veittostensuo, Finland in 1993. The upper peat layer was mass stabilized or column stabilized so that columns were side by side. The lower clay layer was column stabilized (**Figures 12** and **13**). The mass stabilization was the first peat mass stabilization ever performed nationally and probably worldwide. The built embankment served as a part of development project on developing feasible and cost-efficient foundation methods for roads built on swamp areas [51].

The construction works were carried out in demanding conditions. The maximum thickness of the peat layer was 5 m, summed up with the clay layer beneath the thickness of the soft soil layer was up to 25 m. The water content of the intact peat was 1300–1700% and the shear strength was 7–25 kPa [51].

A surface area of $13 \times 18 \text{ m}^2$ was mass stabilized to a depth of 3 m using two different binder agents. The used binder agents per treated peat volume were combinations of rapid cement 125 kg/m^3 + gypsum-based Finnstabi® 125 kg/m^3 and rapid cement 150 kg/m^3 + blast furnace slag 150 kg/m^3 [33].

The designed target shear strength after a year was 50 kPa and the quality of the mass stabilization was assured by in situ soundings, settlement plates, and sampling. The achieved shear strength after a year was 60–100 kPa and exceeding the target value [33]. The quality control soundings were repeated in 2016, after 23 years from the mass stabilization. It was concluded that the strength of the mass stabilized material had increased substantially with both binder agents during the observed period of time. The settlements were also measured during the 23 years period—no significant settlements were observed for the last 20 years. The taken samples indicated that the pH had decreased approximately a unit between 1 and 23 years from the mass stabilization, still exceeding value 11. The water content had also increased significantly in the same period of time [24].

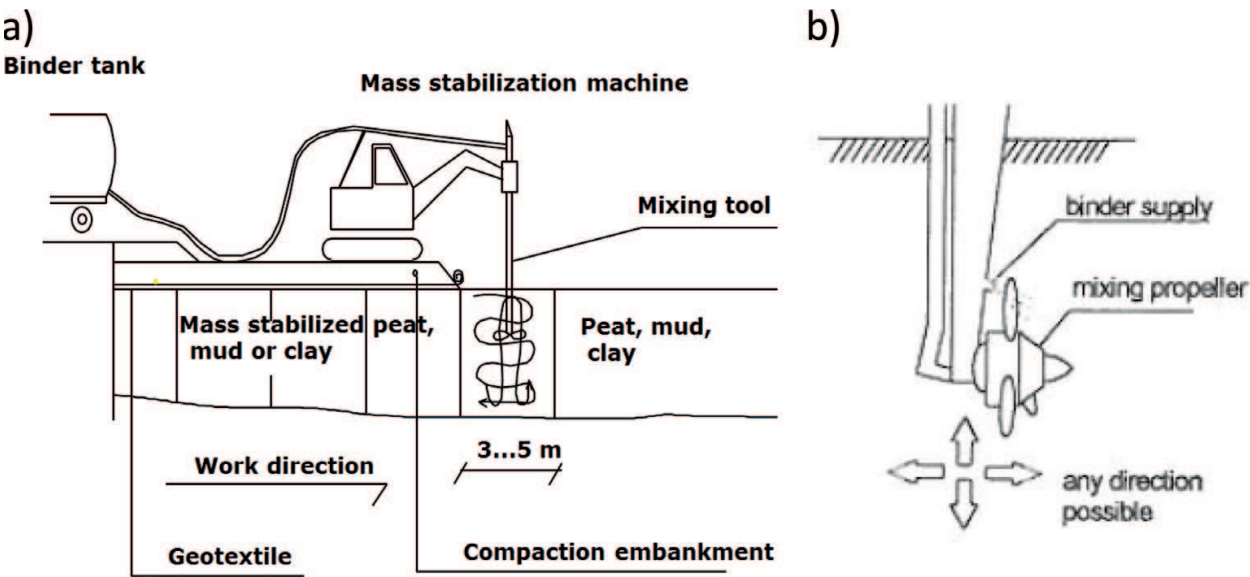


Figure 12. Mass stabilization equipment used in Veittostensuo (a) and the mixing tool (b) ([42] modified [32]).

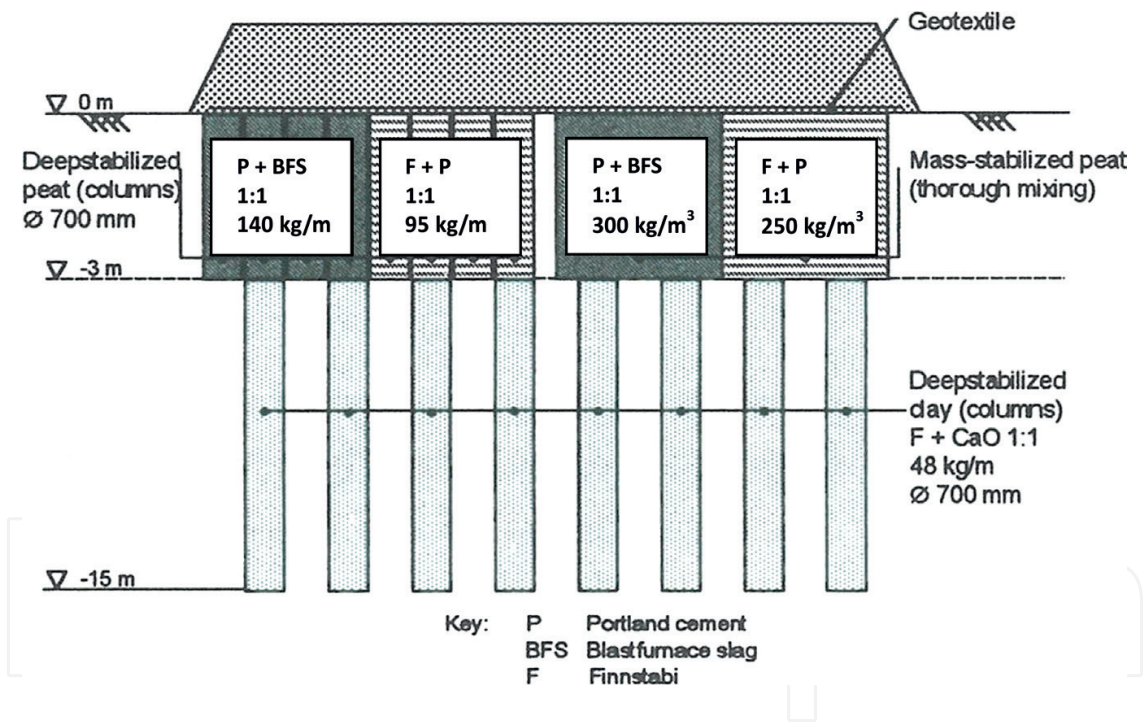


Figure 13. The principle cross section of the combined mass and column stabilization in case Veittostensuo [49].

The case Veittostensuo was a success and embraced the feasibility of the mass stabilization as a ground improvement method; the expectations were exceeded in both short- and long-term studies [24, 33].

10. Summary

Mass stabilization has been used as a ground improvement method in versatile applications for construction at soft soil areas during last 25 years in 25–30 countries. In many of those

cases, mass stabilized soil is peat. The development of equipment has been active and can currently be considered to be technically on a high level. The equipment is relatively light, mobile, and therefore easy to use in various locations.

Various long-term studies have demonstrated that the strength of stabilized peats has increased in average 1.6 times compared to the strength observed after 1 month. Similarly, the settlements have mainly ceased, indicating that creep of the stabilized masses is negligible, approximately 5–8% of the creep of untreated peat. Therefore, it can be concluded that the long-term behavior of mass stabilized peat is stable. However, it is emphasized that preliminary stabilization tests should be completed in the laboratory to ensure that the optimum binder and addition rate are chosen for the execution of mass stabilization.

Mass stabilization method is used to replace mass exchange or piling or other alternative methods. Compared to other methods, it is particularly economical in cases where the driving distances for the excavated peat are long, there is not enough material to replace the excavated peat, or there is insufficient space for landfilling. The binder constitutes the largest part of the unit price in mass stabilization. The CO₂ emissions of the binder (e.g. cement) are often high, but because of the added binder, stabilized peat has a large uptake potential of CO₂. The amount of cement in binder can be reduced or optimized, if recycled materials (e.g. fly ash) are used as part of the binder mixture. In the first hand, stabilization is an environmentally friendly method as it saves natural resources, it does not require landfill areas, and it substantially reduces transportation needs and related emissions. However, more research is needed to more accurately complete a life-cycle assessment taking into consideration the reduction of CO₂-equivalent emissions of the untreated swamp masses.

Thus, sufficient experience exists to conclude that mass stabilization is a beneficial and acceptable ground improvement method for peats. It has proven to be a flexible, cost-effective, environmentally friendly, and stable treatment for peat layers.

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References

- [1] Helenelund K. Geotechnical peat investigations. Proceedings of the First Baltic Conference on Soil Mechanics and Foundation Engineering. Vol 1. Gdansk, Poland, Sep 22-25, 1975. pp. 106-123
- [2] Munro R. Dealing with bearing capacity problems on low volume roads constructed on peat. Including case histories from roads projects within the ROADDEX Partner Districts.

- ROADDEX II Northern Periphery. The Highland Council. Inverness. Scotland. 2004. 136 p. Available from: http://www.roadex.org/wp-content/uploads/2014/01/2_5-Roads-on-Peat_1.pdf
- [3] Forsman J, Jyrävä H, Lahtinen P, Niemelin T, Hyvönen I. Mass Stabilisation Handbook. 2015. 68 p. Available from: <http://projektit.ramboll.fi/massastabilointi//handbook.html>
- [4] Duggan A, McCabe BA, Clifford E, Goggins J. Carbonation in stabilised peat: An accelerated pilot study. Proceedings of the 16th European Conference on Soil Mechanics & Geotechnical Engineering, Edinburgh. Vol. 5. Sep 13-17, 2015. pp. 2383-2388
- [5] Carlsten P. Torv – geotekniska egenskaper och byggmetoder (In Swedish). Information 6. Linköping, Sweden: Statens geotekniska institut.; 1988. 36 p. ISSN: 0281-7578. Available from: <http://www.swedgeo.se/globalassets/publikationer/info/pdf/sgi-i6.pdf>
- [6] Kivinen E, Pakarinen P. Peatland areas and the proportion of virgin peatlands in different countries. In: Proceedings of the 6th International Peat Congress. Duluth. USA: International Peat Society; 1980. pp. 52-54
- [7] Virtanen K, Hänninen P, Kallinen R-L, Vartiainen S, Herranen T, Jokisaari R. Finnish peat resources. 2000. (In Finnish). Geological Survey of Finland. Research Report 156, 2003. p. 102. Available from: http://www.gtk.fi/_system/print.html?from=/_system/PressReleases/news_0206.html
- [8] Kauranne L, Gardemeister R, Korpela K, Mälkki E. Rakennusgeologia II (Engineering Geology II). Otakustantamo; Vol. 304. 1972. ISBN: 951-671-017-4
- [9] Von Post L. Sveriges Geologiska Undersöknings torvinventering och några av dessas hittills vunna resultat (In Swedish). Svenska Mosskulturföreningens Tidskrift. H. Halls boktryckeri-Aktiebolag. Jönköping, Sweden. 1922. 27 p
- [10] Macfarlane I. Engineering Characteristics of Peat. Muskeg Engineering Handbook. Muskeg Subcommittee on Geotechnical Research. Canada: University of Toronto Press; 1969. 297 p
- [11] Landva A. Geotechnical behavior and testing of peat. [PhD thesis]. Quebec, Canada: Laval University; 1980
- [12] SFS-EN ISO 14688-1. Geotechnical Investigation and Testing. Identification and Classification of Soil. Part 1: Identification and Description. SFS-Handbook 179-1, Finnish Standards Association. Helsinki: SFS; 2008. 107 p
- [13] Lojander M, Forsman J, Takala J. Mechanical Properties of Leteensuo Peat. XII Nordiska Geoteknikermötet, Reykjavík. Vol. 1. Iceland: Reykjavík Icelandic Geotechnical Society; Jun 26-28, 1996. pp. 123-128
- [14] Leino J. Hankasalmella tutkitut suot ja niiden turvevarat. (Swamps in Hanksalmi) Part 1 (In Finnish). Geological Survey of Finland. Peat Report 232. 1989. 112 p. Available from: http://tupa.gtk.fi/raportti/turve/ttr_232.pdf
- [15] Ahonen M. Stabiloidun turpeen mekaaniset ominaisuudet (The mechanical properties of stabilized peat) (In Finnish) [Master thesis] University of Oulu; 1993. 61 p

- [16] Helenelund K, Organiska jordartens geotekniska egenskaper (Geotechnical Properties of Organic Soils) (In Swedish). NGF Lecture. Oslo: Norwegian Geotechnical Institute; 1969. 38 p
- [17] Ronkainen N. The Properties of Finnish Soils. Finnish Environmental Institute. Finnish Environment 2/2012. Helsinki. 2012. Available from: https://helda.helsinki.fi/bitstream/handle/10138/38773/SY2_2012_Suomen_maalajien_ominaisuuksia.pdf
- [18] Carlsten P. Vägbyggnad på torv (In Swedish) Vägledning. Vol. 2. Linköping, Sweden: Statens Geotekniska Institut; 1989. 35 p
- [19] Munro R, Sigursteinsson H, Carlsten P, Zweifel G, Pyhähuhta M. Roads on Peat [Web page]. Roadex E-learning, Course 2. 2017. Available from: <http://www.roadex.org/e-learning/lessons/roads-on-peat/peat/> [Accessed: Sep 11, 2017]
- [20] Berry P, Poskitt T. The consolidation of peat. *Geotechnique*. 1972;**22**(1):27-52. DOI: <https://doi.org/10.1680/geot.1972.22.1.27>
- [21] Jelisic N. Mass stabilization, stability and settlement in mass stabilized peat. [PhD thesis]. Department of Soil Mechanics and Foundation Engineering, Lund Institute of Technology; 2002. 168 p
- [22] Van den Haan E, Kruse G. Characterisation and engineering properties of Dutch peats. In: Tan TS, Phoon KK, Hight DW, Leroueil S, editors. *Characterisation and Engineering Properties of Natural Soils*. Taylor & Francis Group; 2007. pp. 2101-2133. DOI: 10.1201/NOE0415426916.ch13
- [23] Leroueil S, Kabbaj M, Tavenas F, Bouchard R. Stress-strain rate relation for the compressibility of sensitive natural clays. *Géotechnique*. 1985;**35**(2):159-180. DOI: <https://doi.org/10.1680/geot.1985.35.2.159>
- [24] Piispanen P. Massastabiloinnin pitkäaikaistoimivuus (Long-term functionality of mass stabilization) (In Finnish) (abstract in English) [Master thesis]. Aalto University, School of Engineering; 2017. 93 + 23 p
- [25] Forsman J. Geovahvistutkimus. Koerakenteiden loppuraportti 1996...2001. (Georeinforcement-project, final report of test structures 1996...2001) (In Finnish). Finnish Road Administration. Finnra Reports 75/2001. ISBN 951-726-833-5, ISSN 1457-9871. 118 p. Available from: https://julkaisut.liikennevirasto.fi/thohje/pdf/3200721_01.pdf
- [26] Forsman J, Dettenborn T, Skepast P, Mets M, Olep M, Ellmann A, Vallas I, Tõnts T, Kontson K. Full scale reinforced road embankment test sections over soft peat layer, Võõbu, Estonia. In: *Proceedings of 17th Nordic Geotechnical Meeting*, Reykjavik Iceland; May 25-28, 2016. pp. 1279-1288. Available from: http://www.ngm2016.com/uploads/2/1/7/9/21790806/139-174-ngm_2016_-_full_scale_reinforced_road_embankment_test_sections_over_soft_peat_layer_forsman.pdf
- [27] Forsman J, Marjamäki T, Jyrävä H, Lindroos N, Autiola M. Applications of mass stabilization at Baltic Sea region. In: *Proceedings of 13th Baltic Sea Geotechnical Conference Historical Experiences and Challenges of Geotechnical Problems in Baltic Sea*

- Region. Vilnius: Lithuanian Geotechnical Society; Sep 21-24, 2016. pp. 241-247. ISBN: 978-609-457-957-8
- [28] Tielaitos (Public Roads Administration): Vt12 Veittostensuon syvästabilointi (The deep mixing of Highway 12 Veittostensuo). Research Report, Investigations of Public Road Administration 81/1993. Oulu (In Finnish). ISSN: 0788-3722. ISBN: 951-47-8761-7.1993. p. 87
- [29] Janz M, Johansson S-E. The function of different binding agents in deep stabilization. Swedish Deep Stabilization Research Centre. Report 9. Linköping, Sweden. 2002. ISSN: 1402-2036. Available from: <http://www.swedgeo.se/globalassets/publikationer/svensk-djupstabilisering>
- [30] Babasaki R, Terashi M, Suzuki T, Maekawa A, Kawamura M, Fukazawa E. Factors influencing the strength of improved soil. In: Proceedings of the 2nd International Conference on Ground Improvement. Vol. 2. May 14-17, 1995, Tokyo; 1995. pp. 913-918
- [31] Åhnberg H. Strength of stabilized soils – A laboratory report on clays and organic soils stabilized with different types of binders [Doctoral thesis], Lund University. 2006. 80 p. Available from: <http://www.swedgeo.se/globalassets/publikationer/svensk-djupstabilisering>
- [32] Huttunen H, Kujala K, Vesa H. Assessment of the quality of stabilized peat and clay. In: Yonekura R, Terashi M, Shibasaki M, editors. Second International Conference on Ground Improvement Geosystems, Tokyo, May 14-17, 1996. Grouting and Deep Mixing, Balkema. 1996. pp. 607-612. ISBN 90 5410 805 3
- [33] Tielaitos (Public Roads Administration): Veittostensuon koerakenteen toiminta ja laadun arviointi (The analysis and assessment of quality of test embankment in Veittostensuo) (In Finnish). Research Report, Investigations of Public Road Administration 54/1995. Oulu. 1995. 51 p. ISSN: 0788-3722. ISBN: 951-726-070-9
- [34] Huttunen H, Kujala K. On the stabilization of organic soils. In: Yonekura R, Terashi M, Shibasaki M, editors. Second International Conference on Ground Improvement Geosystems, Tokyo, May 14-17, 1996. Grouting and Deep Mixing, Balkema. 1996. pp. 411-414. ISBN: 90 5410 805 3
- [35] ALLU PM & PF Stabilisation System, New concept for soil improvement. 2010. Prochure. 8 p. Available from: http://www.agd-equipment.co.uk/images/articles/large/ALLU_Stabilisation_Brochure.pdf
- [36] ALLU - Advanced mass stabilization machinery for mixing dry binders. 2015. 84 p. Available from: http://projektit.ramboll.fi/massastabilointi//materials/6_allu_stabilization_2015.pdf
- [37] Tomasevic D, Dalmacija M, Prica M, Dalmacija B, Kerkez D, Becelic-Tomin M, Roncevic S. Use of fly ash for remediation of metals polluted sediment – Green remeditation. Chemosphere. 2013;92:1490-1497
- [38] EuroSoilStab. Design guide soft soil stabilisation. Development of design and construction methods to stabilise soft organic soils. European Commission under the Brite-EuRam program of the 4th Framework Program, Project No.: BE 96-3177. CT97-0351. 2002. 94 p

- [39] Valtioneuvoston asetus eräiden jätteiden hyödyntämisestä maarakentamisessa/Government Decree on the recovery of certain waste in earth construction (In Finnish/in English). EU notification version 11.5.2017. Available from: <http://ec.europa.eu/growth/tools-databases/tris/fi/index.cfm/search/?trisaction=search.detail&year=2017&num=194&mLang=DE>
- [40] Liikennevirasto (Finnish Transport Agency). Syvästabiloinnin suunnittelu (Deep stabilization design guidebook) (In Finnish). draft 01/2018 (updating of earlier 2010 guidebook)
- [41] Larsson R. Djupstabiliserin med bindemedelsstabiliserade pelare och masstabilisering. Rapport 17. Svensk Djupstabilisering. 2006. 384 p
- [42] EN 14679+AC. Execution of special geotechnical works. Deep mixing. 2005. 61 p
- [43] Forsman J, Melander M, Winqvist F, Halkola H, Korkiala-Tanttu L. Mass stabilization quality control methods. In: Proceedings of the 19th International Conference on Soil Mechanics and Geotechnical Engineering, Seoul. 2017. pp. 2511-2514
- [44] Melander M. Massastabiloinnin laadunvalvontakairaukset (Mass stabilization quality assurance soundings, abstract in English) (In Finnish), [Master thesis]. Aalto University, School of Engineering; 2017. 94 + 18 p
- [45] Forsman J. Stabilisation project – step by step, designing. In: International Mass Stabilisation Conference Aug 2008–Oct 10, 2008, Lahti, Finland. 11 p
- [46] Forsman J, Korhonen O, Havukainen J, Kreft-Burman K. Mass stabilisation in construction of soft subsoils and in environmental geotechnics at city of Helsinki. In: Rostock 12th Baltic Sea Geotechnical Conference. Rostock: German Geotechnical Society; May 31–Jun 2, 2012. pp. 148-154
- [47] Lahtinen P, Niutanen V. Development of in-situ mass stabilization technique in Finland. In: Deep Mixing 2009 Okinawa Symposium, Okinawa, Japan. May 19-21, 2009
- [48] Havukainen J, Leppänen M, Piispanen A. Stabilization of TBT-sediment in a harbour in Helsinki. Ground Improvement. 2011;164(GI1):139-150
- [49] Hoikkala S, Leppänen M, Lahtinen P. Mass Stabilization of Peat in Road Construction. XII Nordiska Geoteknikermötet NGM, Reykjavík. Vol. 1. Iceland: Reykjavík Icelandic Geotechnical Society; Jun 26-28, 1996. pp. 391-395
- [50] Jelisic N. Masstabilisering (Mass stabilization) (In Swedish). Lunds Universitet, Department of Soil Mechanics and Foundation Engineering. 2000. 154 s
- [51] Ravaska O, Kujala K. Settlement calculation of deep stabilized peat and clay. In: Yonekura R, Terashi M, Shibasaki M, editors. Second International Conference on Ground Improvement Geosystems, Tokyo. Grouting and Deep Mixing. May 14-17, 1996. pp. 551-555
- [52] Andersson R, Carlsson T, Leppänen M. Hydraulic cement based binders for mass stabilization of organic soils. In: Soft Ground Technology, Leeuwenhorst Conference Center, Noorwijkerhout, The Netherlands, May 28–June 2, 2000
- [53] Juvankoski M, Törnqvist J. KT51 Kirkkonummen syvä- ja massastabiloitu koerakenne. Loppuraportti. (The Kirkkonummi test embankment on deep and mass -stabilised subsoil)

- (In Finnish). Finnish Road Administration. Finnra Reports 29/2003. 2003. 156 + 98 p. ISBN: 951-803-080-4. TIEH 3200817
- [54] Ilander A, Forsman J, Lahtinen P. Combined mass- and column stabilisation in Kivikko test embankment – Designing by traditional and FE-methods. In: Dry Mix Methods for Deep Soil Stabilisation. Stockholm. Oct 13-15, 1999. pp. 185-191
 - [55] Länsivaara T, Forsman J. Back analysis of Kivikko test embankment. In: Proceedings of the 15th International Conference on Soil Mechanics and Geotechnical Engineering, Istanbul. Vol 1: Aug 27-31, 2001. pp. 441-444
 - [56] Puumalainen N, Halkola H, Rantala K, Forsman J, Hautalahti P. Mass stabilisation and combined mass and column stabilisation in Kivikko area, Helsinki. NGM 2004, May 19-21, 2004, Ystad, Sweden. 2004
 - [57] ALLU Stabilisation System, Sales Manual. 2005. 50 p
 - [58] Ojala AS. Turpeen massastabilointi (Mass stabilisation of peat) (In Finnish). [Diploma thesis], Tampere Technical University; 2002. 103 p
 - [59] Carlsten P, Olsson M. Masstabilisering av torv på riksväg 44. In: Nordiska Geoteknikermötet, NGM, Ystad. Linköping, Sweden: Swedish Geotechnical Society; May 19-21, 2004
 - [60] Koivisto K, Forsman J, Leppänen M. Column and mass stabilisation of the yards of IKEA in Vantaa, Finland. In: Nordiska Geoteknikermötet, NGM, Ystad. Linköping, Sweden: Swedish Geotechnical Society; May 19-21, 2004
 - [61] Forsman J, Koivisto K, Leppänen M. Case stories, industrial and commercial areas – Deep stabilisation of the yards of IKEA in Vantaa, Finland. In: International Mass Stabilisation Conference 2008, Lahti, Finland. Oct 8-10, 2008
 - [62] Ratahallintokeskus (Railroad Administration). Tampere-Seinäjoki, nopeuden nosto, koerakennuskohde N:O 90 (Km 320 + 400-320 + 700), Laadunvalvonta ja asiantuntijatyön raportti, Dnro 2872/52/04, Rataosa 1302 (Tampere-Seinäjoki railroad, test construction report) (In Finnish). 2005. 34 p. + app
 - [63] Maijala A, Forsman J, Lahtinen P, Leppänen M, Helland A, Håøya A-O, Konieczny M. Cement stabilization and solidification – STSO review of techniques and methods. Binders, methods and techniques to stabilize/solidify polluted soil and sediment. 2009. 57 p. Available from: <https://clu-in.org/download/techfocus/stabilization/ramboll-mixing-head-stabilizationRap-001-Id-01-SoA-01.pdf>
 - [64] Forsman J, Hakari M, Jyrävä H, Ritsberg K, Skepast P. Mass stabilisation of E263 Highway section Kose-Mäo in Estonia. In: XXVII International Baltic Road Conference, Riga, Latvia, Aug 24-26, 2009
 - [65] Ronkainen M, Pototski A, Puhkim H, Lahtinen P, Niemelin T. OSAMAT – Utilisation of oil shale ashes in road construction. In: The XXVIII International Baltic Road Conference, Vilna, Liettua, Aug 26-28, 2013

- [66] Markusson M. Peaty ground – Made for mass stabilization. In: NGM 2016 Reykjavik Proceedings of the 17th Nordic Geotechnical Meeting Challenges in Nordic Geotechnic. Iceland: Reykjavík Icelandic Geotechnical Society; May 25-28. pp. 905-912
- [67] Hautalahti P, Halkola H, Puumalainen N. Kivikon teollisuusalueen stabiloinnin koerakentaminen. (Full-scale stabilization tests in Kivikko) (In Finnish). Publication 92/2007 of the Geotechnical Department of the City of Helsinki, Finland. 2007. 85 + 16 p. ISSN: 1458-2198, ISBN: 978-925-223-008-9

