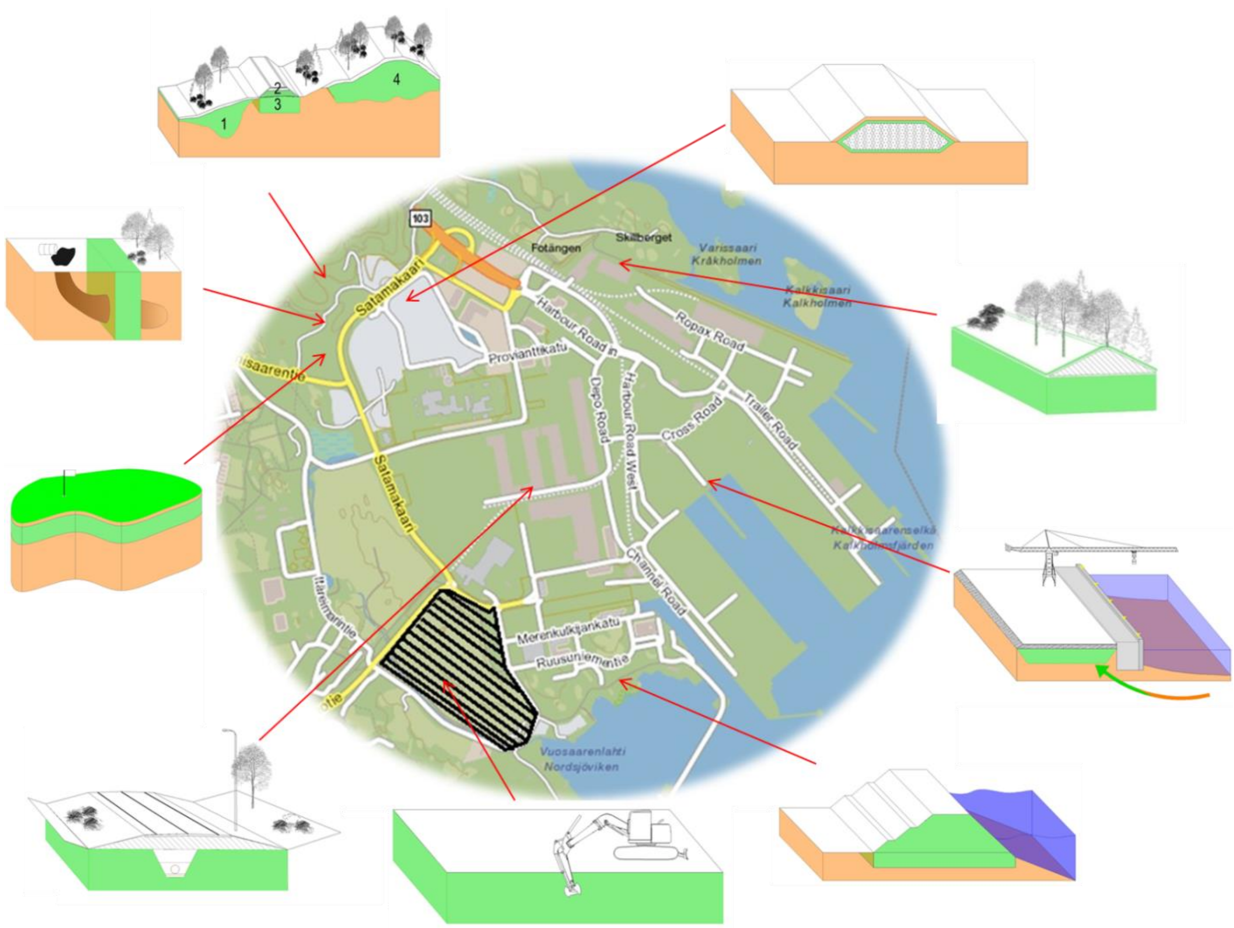
Mass stabilization manual



RAMBOLL

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Table of Contents

FOREWORD

The mass stabilization method and equipment prototypes needed for its application were developed in Finland, in the beginning of the 1990s. Starting from the year 1993, the first large applications had included mass stabilization of peat areas in some road and railway line construction works in Finland and Sweden. Good experience acquired through those projects has led to the expanded possibilities of application for this method. Since 1996, mass stabilization has been also employed for processing soft/ polluted dredged sediments allowing for their further utilization as a material in various port development construction activities. The past decade brought fast development of mass stabilization equipment, binders and various new applications. The method has been implemented in numerous countries, in various infrastructure and environmental engineering applications proving to be an economic and eco-efficient solution.

The objective of this Mass Stabilization Handbook is to promote the use of this method. The manual offers basic information on the mass stabilization method and equipment, as well as practical instructions on the issues concerning binder, ground survey, design, construction and quality control. The manual is meant to serve the needs of all the parties involved in a stabilization project, including developers, permitting authorities, ground investigators, designers, contractors, quality controllers, binder and equipment suppliers and researchers.

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1. INTRODUCTION

Mass stabilization is the process of utilizing chemical admixtures and stabilizing agents to alter the engineering properties of a soil mass so that cost-effective development results are achieved. The goals of the mass stabilization programme are typically to improve the geotechnical engineering performance of a given subgrade, or to achieve environmental performance objectives. The application of mass stabilization techniques alters the technical engineering and environmental properties of soft soil in such a way that it is possible to construct directly on top of the stabilized soil or to utilize it as filling or construction material. Owing to the development of versatile binders, various kinds of soft soils can be stabilized in a cost-effective way.

All mass stabilization projects utilize a binder, or chemical stabilizing agent which reacts with the soil mass to change its properties. 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 use of various industrial by-products as binders in mixtures with commercial binders enables cost-effective application of the mass stabilization method.

This manual introduces the mass stabilization technique, design using mass stabilization, and case studies. The mass stabilization technology, machinery, and applications for methodology are presented in Section 2. These applications embrace the *in-situ* (mixed in place) and *ex-situ* (removal, stabilization, and re-use) use of the method. Section 2 also contains comparisons of the mass stabilization technique with other recognized geotechnical construction practice, focusing on applications that will have growing potential in coming years.

Section 3 presents the technical process of mass stabilization and its effects on commonly measured soil index properties.

Chapter 4 concentrates on detailed description of a variety of previously implemented technical and environmental applications, which have yielded significant positive experience. Some examples of mass stabilization applications including basic technical information are presented as annexes. These applications indicate that in all cases where construction takes place in the sites with soft soils, mass stabilization should be considered as an alternative. The benefits of the mass stabilization method are usually emphasized while turning a soft soil area into a plot suitable for construction. The so-called preconstruction of an area with the mass stabilization method makes the continuation of construction works significantly easier.

A typical mass stabilization project includes a multi-disciplinary approach and close cooperation between various design disciplines. The engineer typically cooperates with the land developer and local development regulatory authorities to realize basic development parameters. During the mass stabilization design, the contractor, ground investigator, binder supplier, and the laboratory work closely together to determine the optimum programme. An overview of the entities typically involved in a mass stabilization project is presented in Figure 1.1 and the roles of participants are summarized in Table 1.1.

Figure 1.1 Parties involved in mass stabilization project.

Table 1.1. Mass stabilization project: parties involved and their tasks.

Party	**Task**
Developer	Setting functional requirements (settlement, bearing capacity, size of the mass stabilized area,…), competitive bidding and contracting for design and construction
Ground investigator	Investigating the structural layers, their thickness and the properties of subgrade
Laboratory	Examination of stabilization properties, creating binder recipes (strength, rigidity), investigating other technical properties (water permeability, leaching, …)
Designer	Preparing site investigation and mass stabilization plans, preparing contract documents (together with the developer)
Contractor	Implementation of the mass stabilization work (as a prime contractor or a subcontractor)
Quality controller	Quality control of the stabilization work and its final product (guiding and verifying)
Authorities	Legal stipulations, authorities' requirements and guidance for stabilization work. Environmental permitting (contaminated soils, use of waste as binders ,…)
Binder supplier	Delivering binder to construction site, binders' development
Equipment supplier	Stabilization equipment construction, maintenance and repair
Researchers	Development of mass stabilization method (binders, technique, instructions, etc.)

2. MASS STABILIZATION METHOD AND MACHINERY

2.1 GENERAL OVERVIEW OF THE METHOD

Mass stabilization is a ground improvement method for soft soils such as clay, gyttja and peat. Its intent is to transform soft soil layers into a homogeneous, strong layer to the target design depth by the chemical stabilization and improvement of soil with an admixed binder agent. Stabilization is used to minimize structure settlement during construction and the operation period, thereby improving structural stability and mitigating the risk of collapse. Mass stabilization can be used in combination with other ground improvement methods. This applies to areas where the top layer of peat (or other very soft soil) is placed above clay. The top portion of the soft layer can be treated with mass stabilization to the depth allowed by the reach of the equipment whereas the clay layer can be reinforced by column stabilization, a similar technique in which discrete pillars or columns of soft soil are improved, rather than the entire soil mass.

Currently mass stabilization is carried out with the addition of dry binder, admixed into the soil unit using either bespoke admixing machinery or common construction machinery, depending on the task and its scope.

The general principle of the mass stabilization method is presented in Figure 2.1. With the current equipment, the attachment of a mixing unit to an excavator allows for carrying out stabilization to the depth of 7-8 meters, providing the conditions are favourable. A pressure feeder injects the binding agent (one or two binders, or a binder mixture) through the hose directly to the mixing drums of the mixing unit. The rotating drums mix the binding agent into the ground and simultaneously homogenize the soil. Mixing is executed by moving the mixer unit vertically from the surface to the desired depth, as well as laterally.

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, work proceeds from block to block, with the size of a block between three and five meters square. A working platform is constructed after completion of a block or blocks to enable the excavator to move on into the site. The working platform also serves as a primary compaction embankment. After stabilization work is complete, a preloading embankment is also constructed at the location under which final strength development takes place. Particularly in areas containing peat and organics, the preloading embankment is indispensable to ensure the consolidation of the stabilized material during the strengthening process (cf. curing of cement). The target strength of the mass stabilization is usually achieved over a period of 1…3 months.

The mass stabilization method can also be implemented to solidify excavated or dredged mud. In addition, it can be applied to stabilize contaminated soils or sediments by turning harmful substances into bound, poorly soluble forms. Mass stabilization of excavated or dredged soft-soil masses enables their utilization at the construction site as improved subgrade, or filling and construction material. This allows for avoiding landfilling spoils and reduces requirements for virgin aggregates, together with the associated needs for transportation.

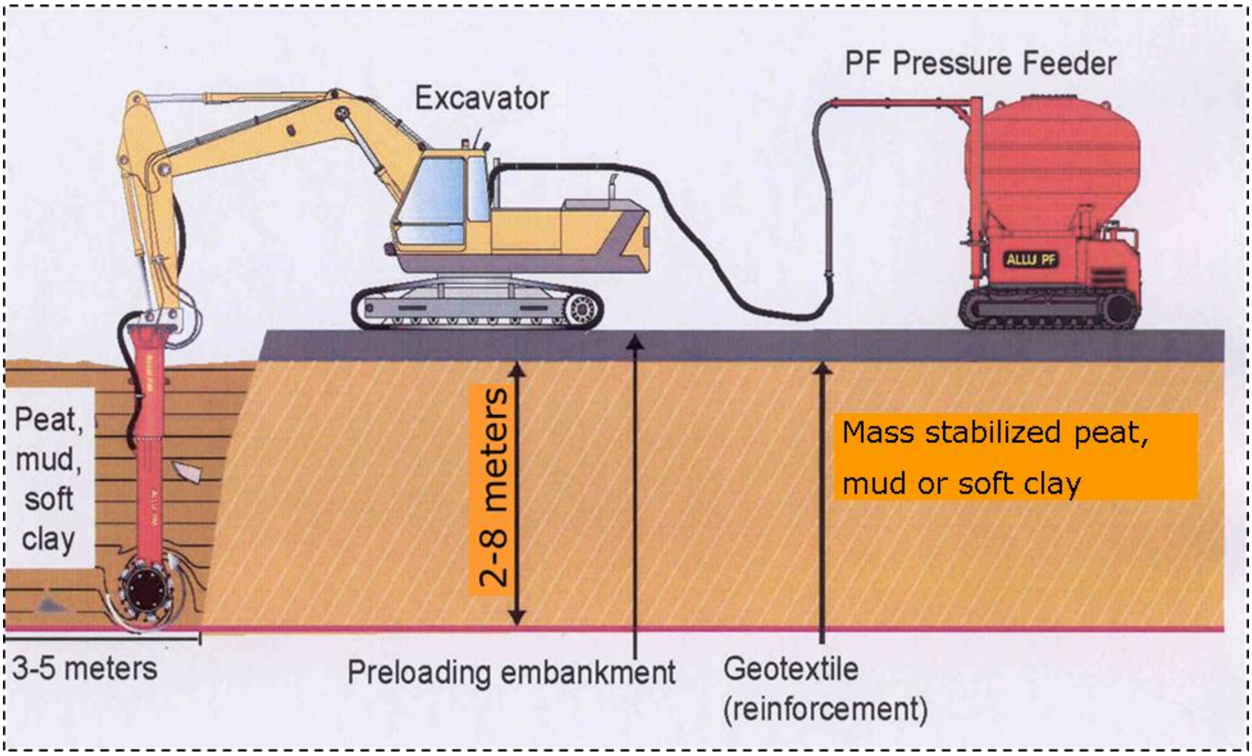


Figure 2.1 Principle of the mass stabilization method and equipment.

The most commonly used binders include cement, lime, or a mixture of both. Additionally, other substances can be added as a binder component. For instance, these include furnace slag powder, fly ash or gypsum. The choice of a binder or a binder mixture depends on soil properties. The optimization of binder quality and quantity is completed in advance in the laboratory.

2.2 BENEFITS

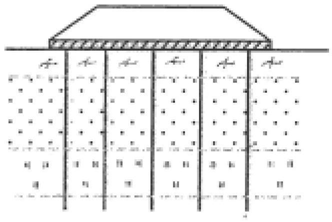
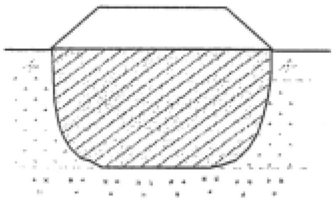
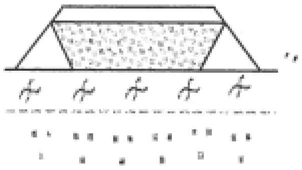
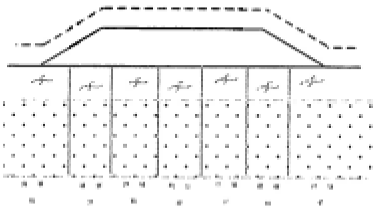
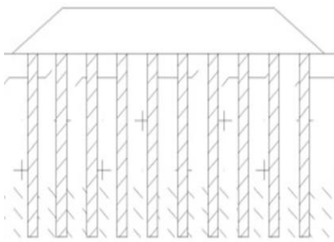
The application of mass stabilization for the treatment of excavated soft or contaminated soils confers significant benefits:

- Low quality masses can be processed with mass stabilization allowing for their utilization, thus minimizing the need for natural aggregates
- Mass stabilization eliminates the need to transport and landfill low quality soil masses
- Mass stabilization of contaminated soils leads to transformation of harmful substances into bound, poorly soluble formations and allows for processing and utilization, thus eliminating the need of soil transportation to contaminated soils landfill

When constructing in soft soil areas, the use of mass stabilization brings various advantages in comparison to other alternative methods. Table 2.1 presents the most commonly observed advantages of mass stabilization as compared to other foundation engineering methods.

Table 2.1. Advantages of mass stabilization as compared to some other foundation engineering methods.

Foundation construction method	Advantages of mass stabilization
Piling	Mass stabilization is usually cheaper than piling, as piles must be installed to deeper levels, and piling requires concrete slabs or pile caps. In the areas with very soft subgrade, mass stabilized layer sometimes serves as a

	working platform for piling, thus enabling piling process to be carried out.
Mass replacement 	Mass stabilization allows for avoiding soft soils replacement resulting in reduced transportation and landfilling needs. Mass replacement requires considerably more natural aggregates than mass stabilization and produces more spoil that overburdens landfill capacity. Mass stabilization provides an economically feasible alternative to mass replacement. Mass stabilization is more risk-free to surrounding structures than mass replacement. It is also often technically a more reliable solution than mass replacement. In the areas with sulphide clay soils, excavated masses deployed above the groundwater level may pose environmental risk. The application of mass stabilization obviates the need for excavation and placing the risky soils above the groundwater surface.
Reduced weight of embankment 	In many cases, adverse settlements can be eliminated more effectively and with less risk via mass stabilization §compared with the load relief method. The use of load relief, where the load on the subgrade is not increased with the load of a new embankment, often results in generating soft surplus soils which is not the case when mass stabilization is applied. Installing pipes inside the embankment and their later excavating from the structure, or carrying out excavations through the structure are often problematic.
Vertical drainage 	Vertical drainage structure requires an extended settlement time to achieve the desired effects. In vertical drainage structures there is a great risk of secondary (creep) settlements.
Column stabilization. 	Compared to column stabilization carried out to a certain depth, mass stabilization constitutes a more “slab-like” and reliable solution to handle settlements. Although variations in quality of mass stabilization are often larger than in case of column stabilization, a mass stabilized structure is generally less vulnerable to variations in quality. Mass stabilized clay excavated from the pipe trench is more utilizable as material in earth construction than column stabilized clay. In the areas of very soft soil, mass stabilization is more easily carried out than column stabilization, as the mass stabilization excavator creates a working platform simultaneously with the progress of work. In soft subgrade, the stability of an embankment is more easily achievable with mass stabilization than with column stabilization.

2.3 MACHINERY AND OPERATING PRINCIPLES

The basic unit of mass stabilization machinery is an excavator onto which a separate mixing unit and a pressure feeder are attached (Figure 2.2). The mass stabilizing system comprises the following equipment parts:

- excavator
- mixing unit
- pressure feeder
- control unit
- data acquisition system

Mass stabilization equipment currently in use allows for achieving the maximum depth of 7…8 meters in favourable circumstances, but the maximum depth achievable always depends on working conditions and on the quality of stabilized soil. When deeper mass stabilization is required, it is possible to use column stabilization equipment and make columns intersect each other. The optimal result is achieved for the layer stabilized to the depth of approximately 3…5 meters. However, thinner layers can also be mass stabilized.

During implementation of stabilization, the binding agent is fed into the soil through the head of the mixing unit. The stabilized mass is homogenized at the same time. Mixing is carried out with the rotating drums while the head of the mixing unit is moved both vertically and laterally in the stabilized layer. The whole area to be stabilized is treated in the same way. The aim is to feed dry binder into the mass as evenly as possible.

Depending on the type of mass to be treated, different types of mixing heads can be applied for stabilization work (Figure 2.3). Dry binder is transported into the mixing unit from the motorized pressure feeder using compressed air (Figure 2.2). Feeding of the binder and the mixing process are controlled with the control unit that allows for adjusting, for instance, the amount of air and the binder flow. These issues have an impact on feeding pressure. It is also possible to adjust the speed of rotating drums. Moreover, the stabilization depth and the amount of mixing work are controlled for each stabilization block. Commonly, mass stabilization is carried out on a grid measuring about three to five meters square. It is also possible to use a separate controlling unit that continuously gathers data (Figure 2.4b).

The stabilization efficiency concept is used to describe work efficiency or performance. When evaluating the actual efficiency, various aspects such as disturbances occurring at the site, refueling and other breaks have to be taken into consideration. Mixing efficiency is controlled with the hydraulic system of the excavator. The efficiency of stabilization is also affected by such factors as the amount of binder, the quality of aggregate soil and the fact whether there is a need for pre-homogenization or pre-mixing in the site before the start of actual mass stabilization works. Also, the air temperature, especially in winter has an impact on the stabilization capacity.

A few examples of approximate efficiency levels observed for some typical aggregate types are presented below. The data was gathered in typical conditions. In general, it has been observed that depending on the case and due to some exceptional conditions, there might occur considerable variations in efficiency.

- peat stabilization approx. 100…150 m^3 / h
- clay stabilization approx. 80…100 m^3 / h
- mass stabilization if dredged masses approx. 100…200 m^3 / h
- firm clay or silt stabilization approx. 50…80 m^3 / h

It is imperative that binders fed with the hose of the mixing unit are fine grained and dry in order to allow for their pneumatic transportation with compressed air.

Figure 2.2 Mass stabilization basic equipment with the mixing unit attached to the excavator and connected to the pressure feeder.

Figure 2.3. Mixing drums of the mixing unit used in mass stabilization.

a)

b)

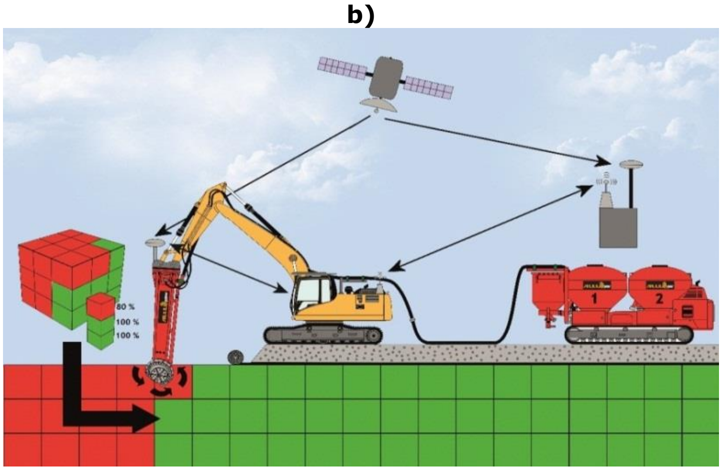


Figure 2.4. Mass stabilization control system a) control and data acquisition system and b) the principle of the 3D-system.

Mass stabilization

- Strengthening method for soft soils
- Intended for curbing or eliminating settlements; improving stability; increasing the stiffness of soft soils; decreasing harmfulness of contaminated soils; and allowing for an easier treatment of soil masses with high water content
- Often a more economical method than the so called conventional foundation engineering methods.

3. TECHNICAL PROCESSES AND THE IMPACT OF MASS STABILIZATION ON SOIL INDEX PROPERTIES

3.1 MASS STABILIZATION TECHNIQUES

Mass stabilization is a versatile method to improve soft soils and soft soil areas. Its main applications can be divided into two groups:

1. Mass stabilization of soft soils on site and in-place = *in situ* stabilization
2. Mass stabilization of excavated / dredged sediments off site = *ex situ* stabilization

Figures 3.1…3.4 present mass stabilization applications with the *in-situ* and *ex-situ* methods. The stabilized subgrade can include clay, gyttja, peat, etc.

1A) Traditional mass stabilization for strengthening such structures as the road or field base in order to prevent harmful settlements and to ensure stability (Figure 3.1A).

1B) In soft soil areas, mass stabilization can also be used to strengthen pipe trenches such that they may remain unsupported during construction, or that bracing elements are sufficient, and that the stabilized soil will serve as an acceptable foundation for the upcoming structure. Moreover, the excavated stabilized soil may be utilized more easily (Figure 3.1B).

1C) Surplus soft soils to be removed can be mass stabilized before excavating and afterwards utilized, for instance, as a material for a noise barrier. Sometimes excavated soils are so soft that transportation becomes a challenge. With mass stabilization in advance, the excavated soft soils are transformed into a more solid form that is easier to be transported (Figure 3.1C).

2A) Soft surplus soils are disposed at a filling area where they are mass stabilized. In this case, mass stabilization can also include the potentially soft layer of clay or peat that is located below the filling (Figure 3.2A).

2B) Dredged masses are placed into a basin confined with embankments and the masses are mass stabilized. Afterwards, the stabilized filling can be used, for instance, as a filling material required for the development process of a harbour area (Figure 3.2B).

3A) Excavated soft soils are mass stabilized in a basin and utilized after strengthening as, for example, a road embankment filling material (Figure 3.3A).

3B) Water- retaining mass stabilized layer can be placed on top of blasted stone filling and beneath the vegetation layer (Figure 3.3B).

3C) Mass stabilized soils can be used as a material for the construction of noise and flood barriers (Figure 3.3C).

4) Dredged masses can be mass stabilized in a barge and utilized afterwards as filling masses disposed at sea or on land (Figure 3.4).

3.2 MASS STABILIZATION INFLUENCE ON SOIL PROPERTIES

<u>Influence on soil index properties</u>

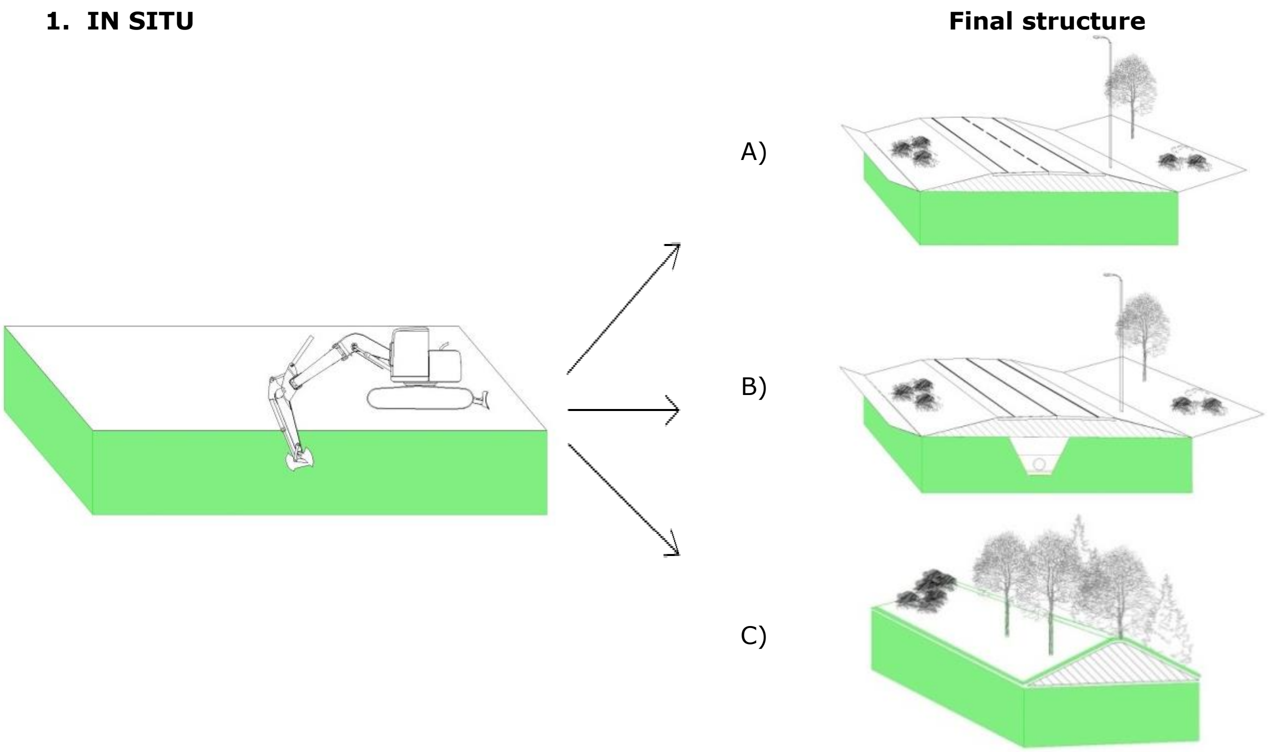
Mass stabilization significantly alters the geotechnical characteristics of soil. The result of the mass stabilization process and its rate of change are influenced by various factors, such as the type of soil, the type and quantity binder used, curing time, temperature and compaction load. Mass stabilization alters the index properties of soil (i.e., water content, plasticity, bulk density, etc.), its strength and compressibility properties, and water permeability. The impact of stabilization on the unconfined compressive strength and deformation is presented in Figure 3.5.

Impacts on environmental properties

Mass stabilization can also be applied in treatment of contaminated soil units. Stabilization binds harmful substances into a poorly soluble form, thus allowing for the utilization or safe disposal of the treated masses. Other applications of mass stabilization include the construction of reactive barriers which bind harmful substances and prevent their spreading into the environment. Various binders and binder mixtures exhibit different properties in the process of binding harmful substances; thus, the proposed binder recipe must always be investigated in the laboratory on a case-by-case basis.

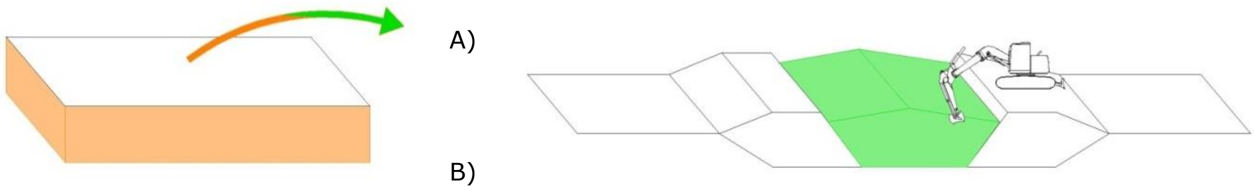
Mass stabilization allows for a decreased spread of harmful substances as a consequence of the following changes in properties:

- retaining and encapsulating of harmful substances
- changes in chemical properties (pH, redox)
- changes in physical properties, including water permeability, binding fine particles into the soil matrix, and decreasing the natural water content



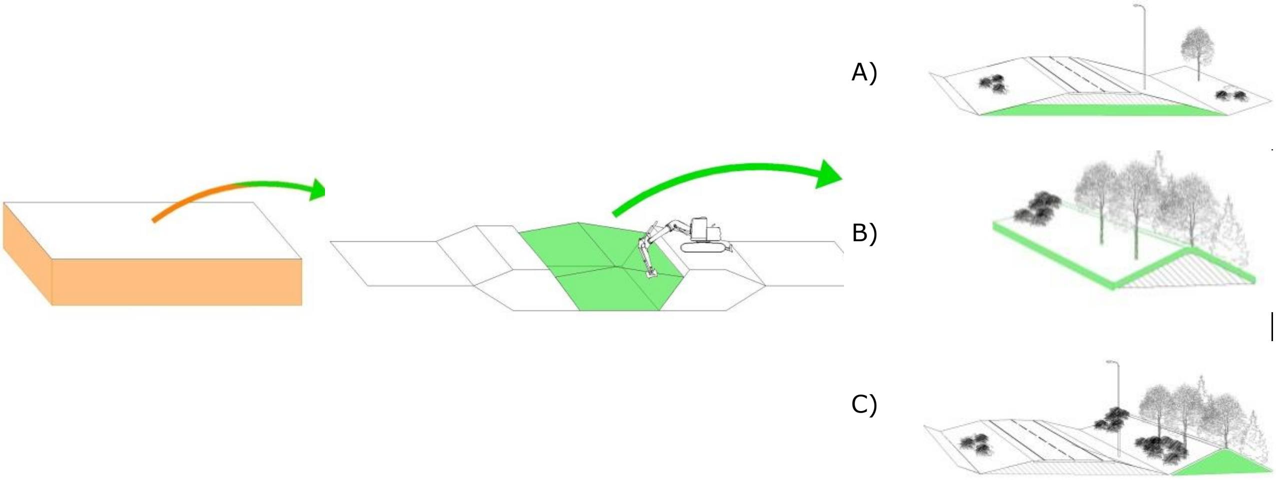
A) Subgrade improvement of a road embankment with mass stabilization
B) Unsupported pipe trench excavated in a mass stabilized soil
C) Soft clay mass stabilized in advance can be excavated and utilized, e.g., in a noise barrier – placed on top of a mass stabilized subgrade

Figure 3.1 In situ mass stabilization as a subgrade improvement and earth construction material.



A) Surplus soils originating from mass exchange are mass stabilized and used as filling.
B) Dredged sediments are disposed in a confined basin. Mass stabilization in the basin and subsequent paving of the area allow for its use as, for instance, a harbour yard material.

Figure 3.2 Ex situ mass stabilization: stabilized mass is utilized in a stabilization basin.



Excavated material is mass stabilized in a basin and after strengthening utilized elsewhere.
A) Road embankment fill
B) Water retaining layer, e.g., on top of blasted rock or a tyre crush filling and beneath the topsoil
C) Noise barrier

Figure 3.3 Ex situ stabilization: material mass stabilized in a basin is utilized elsewhere.

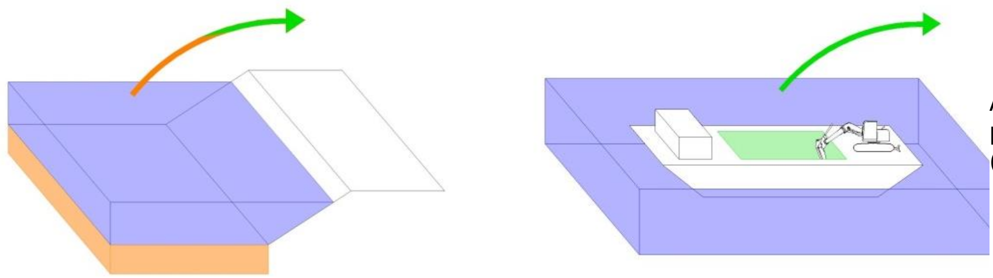


Figure 3.4 Ex situ stabilization: material mass stabilized in a barge is utilized elsewhere.

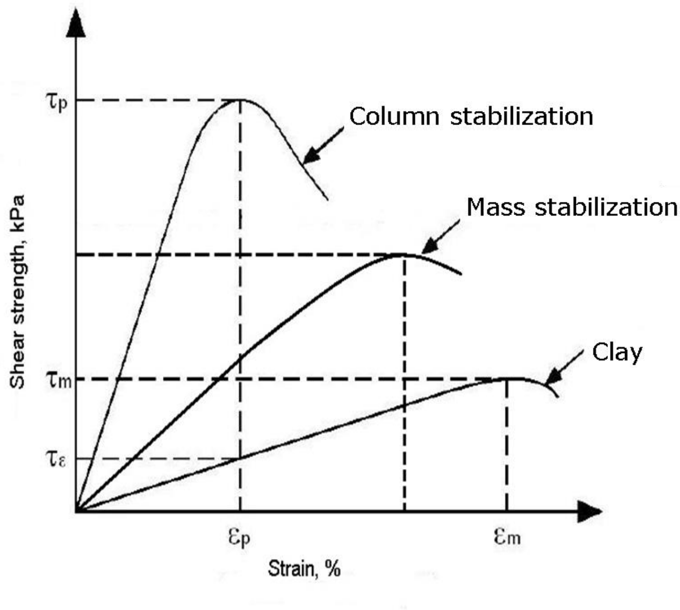


Figure 3.5 The impact of stabilization on the unconfined compressive strength and the deformation of clay.

4. APPLICATIONS OF MASS STABILIZATION

4.1 GEOTECHNICAL APPLICATIONS

Mass stabilization can be used in versatile applications as a subgrade improvement method and as a processing method to allow use of low-quality soil. Typical mass stabilization applications include:

- roads
- streets and pedestrian paths
- railways
- municipal engineering applications
- harbours and sea routes
- landscaping sites (e.g., parks)
- outdoor activity centres
- environmental protection structures
- mining areas
- landfills and waste treatment areas
- industrial and commercial areas
- housing construction areas
- flood protection

Mass stabilization can be completed in the following ways:

- full penetration through the whole thickness of soft soil layers
- partial penetration to a given depth (i.e. a "floating" structure)
- optimized as a combination structure - mass stabilization on top of column stabilization

By mass stabilizing soil fully to the bottom of the soft soil layers, an almost non-settling subgrade improvement result can be achieved (Figure 4.1a).

In the case of partially penetrating mass stabilization carried out to a given design depth, soft soil layers are allowed to remain under the stabilized zone (Figure 4.1.b). In this case, the load induced by the embankment is distributed by the mass stabilized layer to the lower layers, thus creating uniform settlement behaviour and eliminating differential movement. If settling layers remain below the stratum stabilized to a certain design depth, the structure constructed on its top will experience settlement. The magnitude of settlement in a partially penetrating mass stabilization project is significantly affected by the stress level induced by the new construction, particularly if the applied stresses exceed the preconsolidation stress of the lower soft soil unit. Column stabilization carried out under partially penetrating mass stabilization reduces the settlement of the soft soil layers under the mass stabilized stratum and decreases the danger of collapse of the embankment by impeding the formation of a sliding surface (Figure 4.1.c).

Most commonly, the combination of mass and column stabilization is used in the cases when peat or gyttja constitute the uppermost soil layer and the application of the column stabilization method alone would not provide sufficiently strong columns. Mass stabilization can also be applied to provide a working platform for mobilization of column stabilization machinery in the areas with particularly poor subgrade conditions.

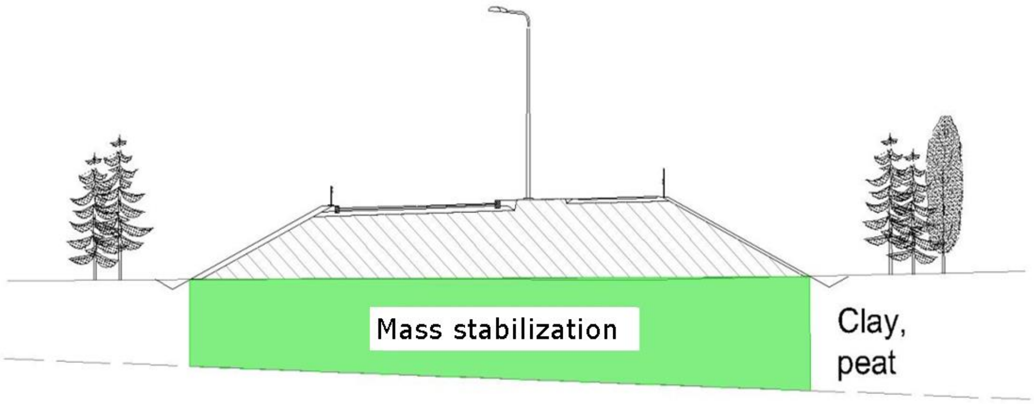
4.1.1 ROADS

In road structures, mass stabilization is typically used as a ground improvement method for soft soils to achieve a bearing foundation that allows for construction of compacted embankment fill and the construction of the final road structural layers. The function of mass stabilization in such cases is:

- to reduce settlement of the subgrade by increasing subgrade layer stiffness
- to improve the total stability by increasing strength of the subgrade
- to increase the load-bearing capacity (improved shear strength)
- to improve the condition of low-quality soils and to increase their utilization potential (stabilization prior to excavation)

In situations where soft subgrade shall be excavated in any case (for instance, mass exchange excavations, underpass digging, or the like), it is possible to stabilize soft soil mass before excavation. In this case mass stabilization eases excavation and improves the quality of the excavated soil mass. The excavated, stabilized soil mass is less difficult to transport and offers greater re-use potential, for instance as embankment filling in landscaping or green area development projects.

a)



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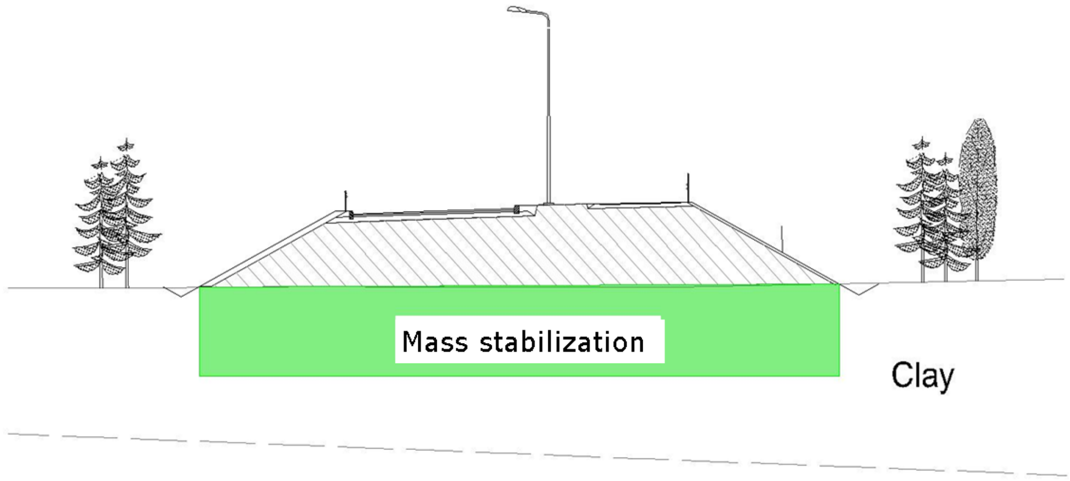

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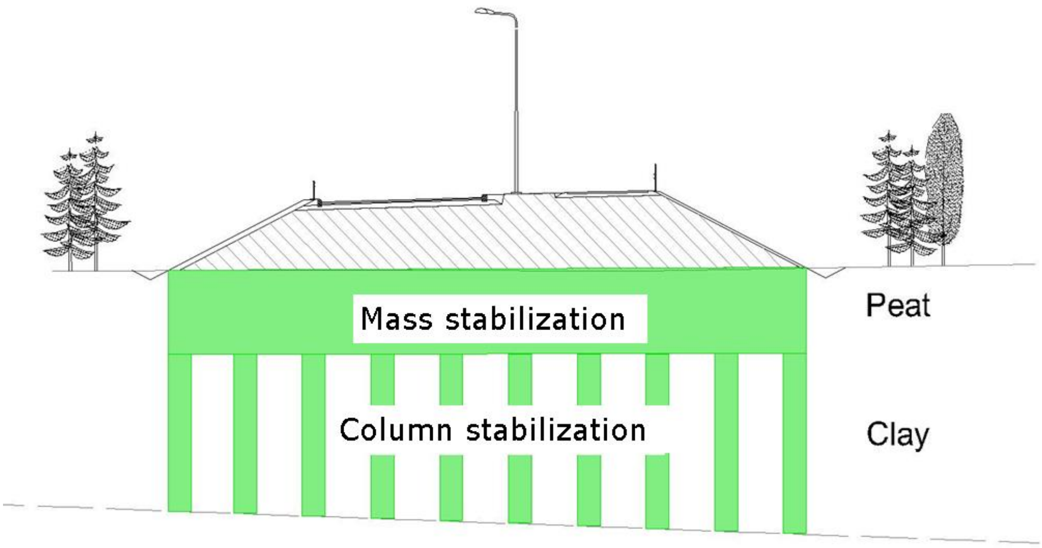


Figure 4.1 Mass stabilization a) in lower level of soft soil layer, b) mass stabilization to a given depth and c) combination of mass stabilization and column stabilization.

a) b)

Figure 4.2 Example of the use of mass stabilization as ground improvement of a road in a marshland area. a) road area before mass stabilization and b) after mass stabilization and construction of the pavement (photo: Leppänen 1995 and 1996).

4.1.2 RAILROADS

Mass stabilization may address various needs in railway line development or repair projects. For instance, it enables the following applications:

- strengthening the ground adjacent to an old railroad embankment built on a soft soil
- ground improvement of a new embankment or existing railroad embankment requiring repair
- constructing a vibration reducing wall
- improving the condition of low-quality soils (stabilization before excavation)

The above-mentioned mass stabilization applications for railroad projects within and near the railroad are shown in Figure 4.3. In Finland, column stabilized walls have been constructed in several sites to restrain ground vibration induced by trains. In appropriate circumstances, a vibration reducing wall can be also constructed with the application of mass stabilization.

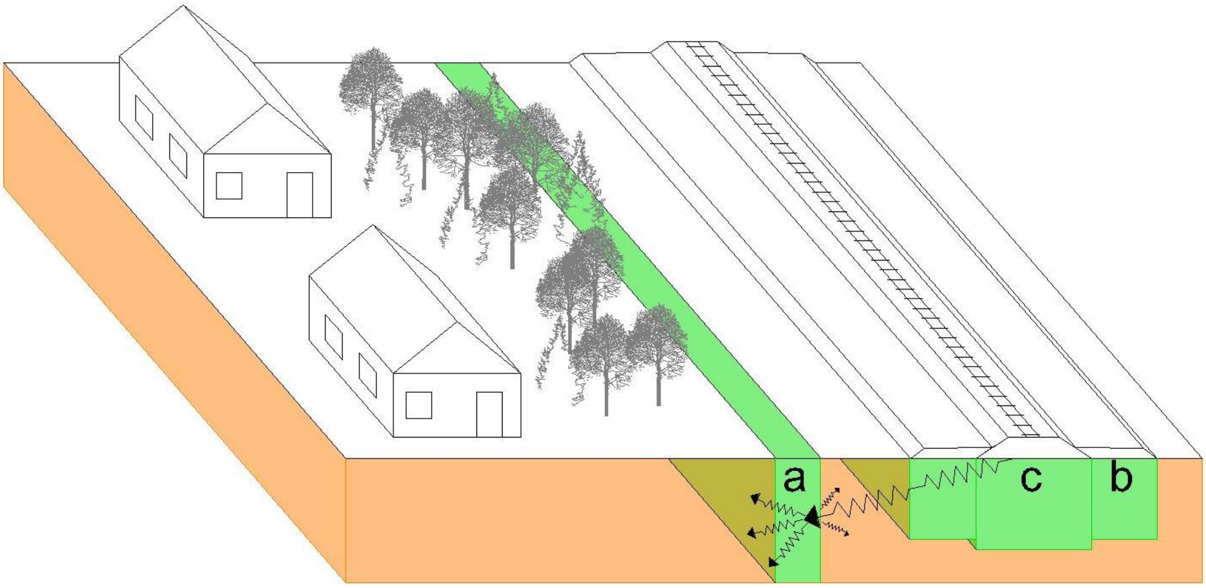


Figure 4.3 Application possibilities of mass stabilization in railroad projects, a) vibration reducing wall, b) improvement of areas adjacent to railroad embankment and c) improvement of subgrade under railroad embankment.

In Finland, there is an abundance of old railroad embankments with low embankment stability. As a result, projects to raise the existing embankment or to improve the track to accommodate newer, heavier rolling stock increase the risk of embankment failure. Therefore, foundation reinforcement measures are required. In case of old railroad embankments, construction of a counter-weight reinforcement embankment is typically a cost-effective solution. Mass stabilization allows for the construction of a counter-weight reinforcement embankment if the strength of the subgrade in the area adjacent to the embankment is not sufficient. Figure 4.3. presents an example of such a structure (Item b).

The first railroad project where mass stabilization was performed to reinforce the ground under the embankment was carried out in 1996, in Sweden, on the Uppsala-Skyttorp line (Figure 4.4.). The peat layer of 2…3m average thickness was mass stabilized using fully penetrating methods to the firm bottom before the construction of a railroad embankment. An example of mass stabilization carried out under a railway yard is presented in Figure 4.5.

a) 

b) 

c)

d)

Figure 4.4 Railway project in Sweden, 1996, a) initial situation – railroad established on a timber grillage b) and c) mass stabilization works in progress in the railroad area d) ready railroad moved to the mass stabilized area. (photo: Leppänen 1996)

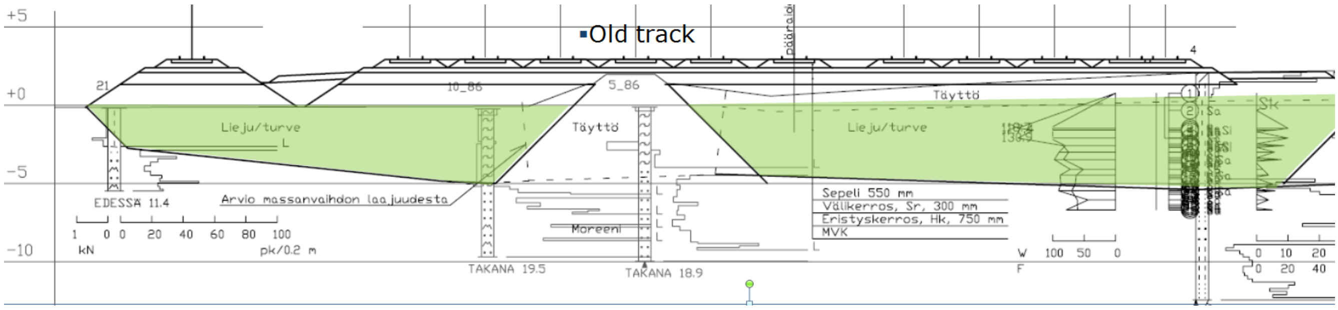
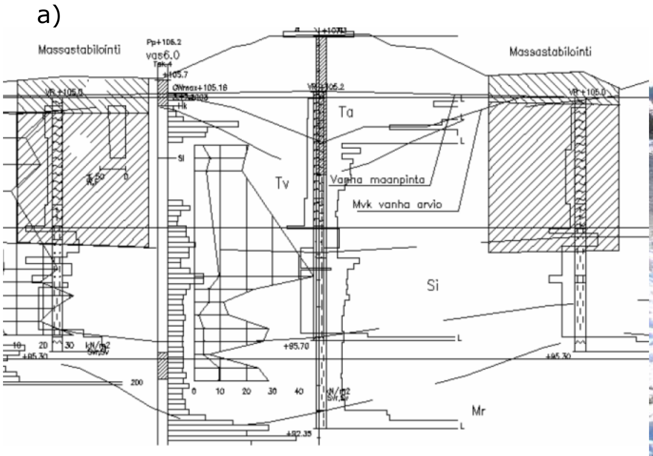


Figure 4.5 Example of mass stabilization carried out in a railway yard (Forsman 2008).

a)



b)

Figure 4.6 Stability of an existing railway embankment was improved by a counter-weight embankment built in the soft soil area treated with mass stabilization prior to the start of construction a) Heikkilä 2006, b) photo: Tikkanen 2006).

4.1.3 STREETS, PEDESTRIAN AND BICYCLE PATHS

As with general road construction applications, mass stabilization can be used as a means of ground improvement in municipal street and pavement building projects. It also allows for the improvement of quality of excavated masses. The essential difference lies in the fact that in the latter case, municipal utilities must be taken into consideration. The maintenance of pipes, cables, etc., requires frequent opening the streets. In the street, pedestrian and bicycle path construction projects, mass stabilization allows for:

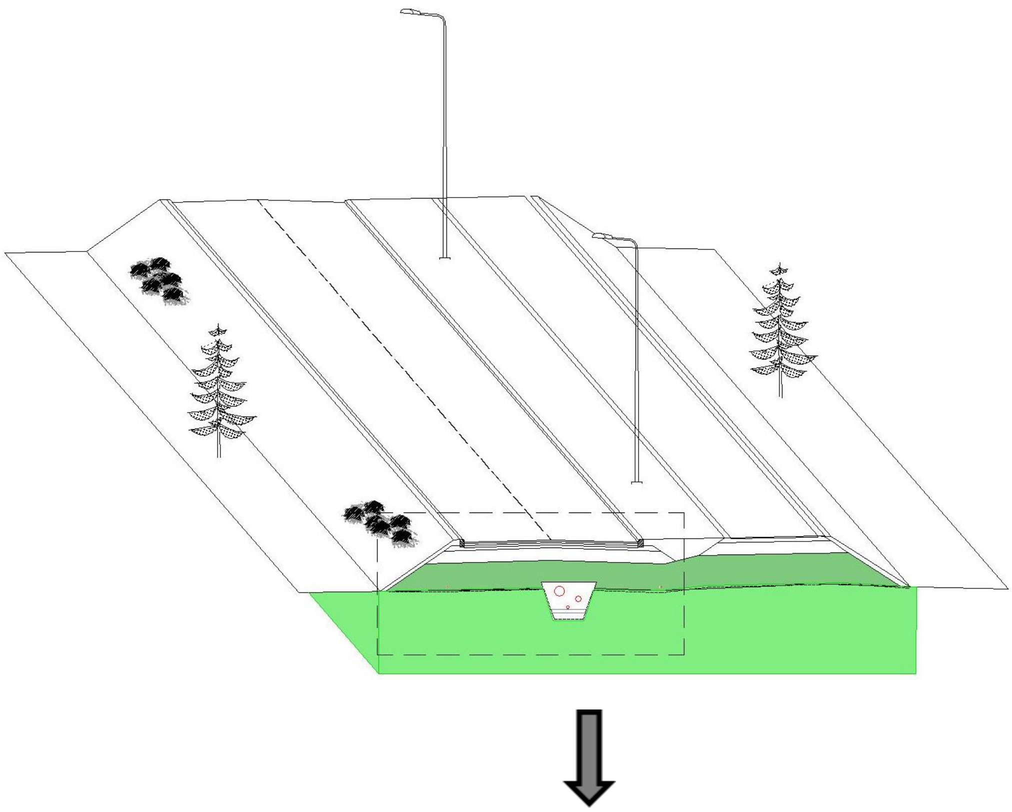
- to reduce settlement of the subgrade by increasing layer stiffness
- to improve the total stability by increasing strength of the subgrade
- to increase the load-bearing capacity (improved shear strength)
- to improve the condition of low-quality soils and to increase their utilization potential (stabilization prior to excavation)

While designing the improvement of a street subgrade, several requirements must be observed and followed. These embrace the requirements for the street structure settlement, digging pipe trenches, and pipe settlement criteria. The requirements for the pipe settlement are generally more stringent than in the case of a street structure alone.

In shallow trenches, providing the conditions allow, pipes can be installed in the stabilized layer of the unsupported trench. In deeper trenches - in the mass stabilized subgrade layer - it is possible to replace the sheet pile support with bracing elements.

To date, the mass stabilization application that has been most rarely employed is utilization of stabilized mass in the pavement layer of a street or a pavement. Figure 4.7 presents the principle of utilizing the mass stabilized soil material in the construction of embankment filling, and the drainage or sub-base layers. In the late 1990’s, in the Viikki district of the City of Helsinki, a trial mass stabilization section was built as part of a street constructed in the area with clay. In this site, the sub-base layer was constructed using mass stabilized clay and no adverse effect of freezing and thawing on the bearing-capacity of this layer was observed.

a)



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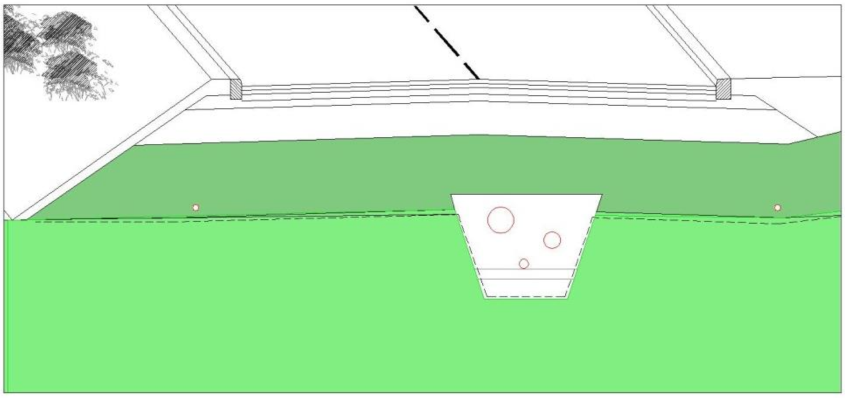


Figure 4.7 Mass stabilized material in embankment filling and in sub-base layer (dark green a) mass stabilization as subgrade improvement (light green, b) unsupported trench for municipal engineering structures dug in the mass stabilized soil.

4.1.4 MUNICIPAL ENGINEERING STRUCTURES AND NETWORKS

Mass stabilization allows for the improvement of pipeline subgrades as well as of the soil layer into which the pipeline trench is excavated. After mass stabilization, settlements in trench lines will be reduced leading to smaller differential settlement and increased reliability of the network as a result.

The advantages of applying mass stabilization to construction of municipal engineering structures and networks include: (Figure 4.7b):

- reducing and equalizing subgrade settlements by increasing the stiffness of the subgrade soil layers
- enabling the construction of unsupported pipeline tranches in soft subgrade
- improving the condition of the excavated poor quality soils (stabilization prior to excavation)
- consolidating soft excavated soils to enable re-use during backfilling works in pipeline trenches

Municipal engineering structures and networks include various different structures with respect to settlement tolerance, ranging from gravity pipes with very stringent requirements to pressure pipes which can tolerate comparatively large settlements. In the case of pipelines which do not tolerate settlement, mass stabilization may be necessary to pre-condition the subgrade so that the embankments constructed on top of the pipes do not cause additional settlements. In this application mass stabilization serves the same objective as traditional pre-loading procedures.

Excavating a pipeline trench in a stabilized soil stratum is easier and safer compared to excavations in soft cohesive soil. The depth of trenches for municipal utilities varies depending on its type and the local climate. Certain types of trenches might be shallow, whereas others as in the case of pumping station shafts must be deep. Mass stabilization strengthens the subgrade, which in favourable conditions allows construction of unsupported trenches or to use support elements. In the deeper trenches where sheet piles are used for support, mass stabilization of the soil layer under the piles provides the opportunity to shorten the length of the piles. Additionally, the improved strength of the soil masses adjacent to the trench may allow piles with reduced bending capacity or steel grade, to eliminate internal support, or a combination of these.

Some municipal engineering structures and networks are placed in greenbelt areas, fields and forests, which allows for potential use of stabilized, poor quality soils for trench backfill. Mass stabilized excavated soil can also be used as backfilling in other trench construction works, however in such cases strength and deformation properties must be determined on a case-by-case basis, taking into consideration the instructions and requirements of the pipeline owner or regulatory authority.

In order to avoid ground- and perched-water flow into the pipeline trenches, a barrier layer made of clay is constructed. To this end, mass stabilized clay can be utilized as a material replacing the traditionally used dry crust clay.

4.1.5 PORTS AND FAIRWAYS

Port development and fairway deepening works generate large amounts of dredged material that does not always allow for disposal at sea due to contamination of the masses. Instead of unconfined open water disposal, dredged sediments can be mass stabilized and utilized in port and harbour development, for instance as filling in a new port yard area. Port development projects offer a possibility to utilize considerable amounts of stabilized soil material. This reduces the amount of fill aggregates that would otherwise be transported to the site from elsewhere.

In cases when dredged sediments are contaminated, leaching of toxic or hazardous substances is generally reduced along with the progress of the stabilization process, which results in the improved environmental acceptability of the dredged masses. Figure 4.8 illustrates a typical example of the port construction application that allows for the utilization of mass stabilized dredged sediments.

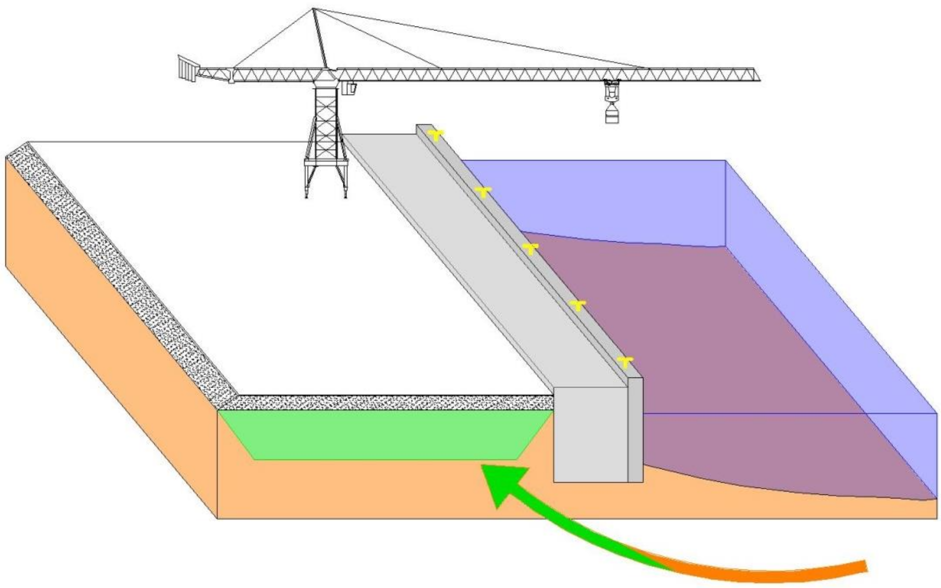


Figure 4.8 Sediments dredged from the sea are mass stabilized and utilized as a filling material in the port field and for the construction of the lower part of the pavement.

For the needs of the stabilization process, commercial binders such as cement can be partially or fully replaced by use of various industrial by-products. The application of industrial by-products as binders is an environmentally friendly solution owing to diminished leaching properties of the dredged masses and the cost-saving merits of recycling otherwise unusable industrial by-products.

Dredged masses are usually first transferred to a basin where the stabilization process takes place. The stabilization basin functions either as a final location site for the stabilized masses or only serves as a mixing basin for stabilization and binder addition, and the stabilized mass is later moved to another target. The quality of the dredged masses and the intended final use of the mass must be considered in the design process of a stabilization basin. The impact of stabilization works on a watercourse is usually minor if the process is carried out in a confined basin with no direct contact to the watercourse (for example, Figure 4.9).

If stabilized dredged mass is eventually utilized in a different site than the stabilization basin, it is transported there after having reached the adequate level of consolidation (often after 1…3 moths of curing time).

In the case when dredged sediments are treated in a basin which constitutes their final disposal site, mass stabilization can be carried out either to the bottom of the basin or as a “floating” structure, where the lower level of the mass remains not stabilized. The choice of the solution depends in each case on the performance requirements set for the final structure. The thickness and quality of the bearing course constructed on top of the stabilized layer depend on the end purpose of the basin site. Generally, such areas function as various port fields or storage areas.

a) b)

Figure 4.9 a) Mass stabilization basins in the Port of Vuosaari (photo: the Port of Vuosaari), b) mass stabilization in progress in the Port of Valencia (photo: ALLU).

a) b)

Figure 4.10 Contaminated dredged sediments a) disposed in a basin confined by an old quay and a sheet pile wall and b) mass stabilized (photo: Deep Soil Mixing Ltd. UK).

Figure 4.11 The Port of Vuosaari: wetland area a) after topsoil clearing and b) after carrying out mass stabilization and the pavement construction (photo: Havukainen 2004).

4.1.6 GREEN AREAS AND LANDSCAPING

Green areas construction generally does not require the use of frost resistant and non-settling material because, depending on the maintenance needs, some minor frost heave and settlement are acceptable. When using stabilized soil masses as filling in green areas development projects, there is a need to address the issues of design, drainage functioning, water permeability of the filling layer, acidity of the stabilized mass, and the layers of the topsoil coming onto the filling.

The requirements for green area development and landscaping projects typically state that the result is sufficient provided that filling material can be spread, shaped and condensed in a constructed structure. Therefore, the amount of binder used for stabilization can be smaller than in a structural application such as those listed in the sections above. The stabilized mass as such is not suitable to function as a growing substrate, therefore there is a need to place the final topsoil layers onto the filling. Their quality and thickness depend on the planned vegetation type (the usual thickness of topsoil is 0,2…0,5 m)

Poor quality and surplus soils after stabilization can be utilized in various applications in green areas development and landscaping projects according to the principles illustrated in Figure 4.12. If necessary, mass stabilization can also be applied to strengthen the subgrade of a wetland.

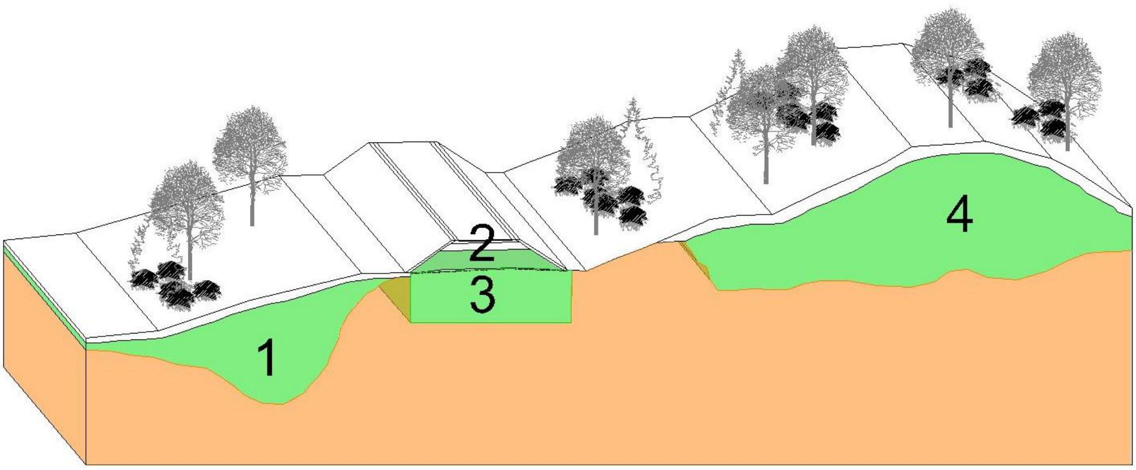


Figure 4.12 Filling carried out with the use of stabilized poor quality, surplus soil in green areas development projects and landscaping: 1) landscaping filling, 2) filling of a path embankment, 3) landscape hillocks and 4) subgrade improvement of a path

Figure 4.13 Ida Aalberg park in Helsinki: a and b) utilization of the deep stabilized masses in landscaping, c) ready park (photo: Aino-Kaisa Nuotio 2013 and 2014).

4.1.7 OUTDOOR SPORT AREAS

In the construction of sport fields, it is essential that drainage provisions in the area function well and sloping is carried out in proper directions preventing ponding problems to occur. For sport field construction in a reclaimed wetland area, mass stabilization commonly proves to be the right solution for subgrade improvement to produce a final surface with the relevant standards and regulations for sport field use.

To achieve the required flatness, a large amount of filling material is often needed. For this reason, construction of sport fields provides a good opportunity to utilize substantial amounts of mass stabilized poor quality, surplus soils. In order to avoid settlement problems, good compaction and preloading are often a necessity.

The types of outdoor sport facilities that allow for the utilization of mass stabilized soils include, among others:

- sport fields,
- football playing fields,
- horse riding fields.

Sport facilities with lower flatness requirements include, for instance, various mountain-bike tracks and ski slopes.

Geotechnical applications of mass stabilization

- improvement of the subgrade in roads, streets, pavements and embankment fillings
- improvement of the subgrade in new and old railroads, as well as railway yards; vibration reducing structures
- reducing settlements in municipal engineering structures, ”supporting” municipal utilities trenches, final fillings
- utilization of dredged sediments resulting from port and fairways deepening works as a filling material in port development projects
- fillings and subgrade improvement in green areas development and landscaping projects
- fillings in construction of outdoor sport areas

4.2 ENVIRONMENTAL ENGINEERING APPLICATIONS

4.2.1 ENVIRONMENTAL ENGINEERING STRUCTURES

The general purpose of environmental engineering structures is to provide various type of protection to housing and industrial buildings, to infrastructure constructions, as well as to other potential human and ecological receptors. Their role is also to protect various ecosystems, as well as ground water and surface water bodies (Figure 4.14).

The typical environmental engineering structures that allow for the application of mass stabilization or the use of the mass stabilized surplus soils include:

- noise barriers
- flood protection structures (dams and embankments, including dam crest or embankment raising)
- reactive walls
- barrier walls (for instance to confine the treatment area for contaminated soils)
- vibration reducing walls (for example, in railroads)
- solidification of contaminated soil masses

In the construction of noise barriers, mass stabilization can be applied to reinforce the subgrade and stabilized surplus soil can be utilized as the wall material. Higher embankments with steeper slopes necessarily require higher strength stabilized masses. If necessary, slope stability can be improved with the aid of geo-synthetics and/or supporting embankments.

Flood protection is defined as the design and construction of permanent structures that eliminate or lower the risk of flood damages. In dams and embankment applications, mass stabilization can be applied as a means of reinforcing the subgrade. Moreover, mass stabilized surplus soils and dredged sediments can be used as the sealing and construction material for building the actual dam or embankment.

Finnish clays are commonly characterized by low water permeability, high water content, low shear strength, and high compressibility under load. Moreover, their suitability for earth construction is poor. Performance and re-use potential can be improved with mass stabilization. Mass stabilization allows to compact clay in a better way and to construct, for examples, a homogenous sealing structure. In case of a sealing layer made of stabilized clay, preliminary tests are essential to determine the proper amount and quality of binding agent. If the amount of binder mixed with clay is too large, it will make the clay layer excessively dry and brittle, thus raising the risk of cracking. Therefore, such a situation should be avoided with the aid of a proper binder recipe to maintain the clay in a plastic, workable state. The composition of binding agents has also an impact on the possibility to achieve the required water permeability.

Mass stabilized clay can be used in a horizontal or inclined seal layer, as well as an insulating material in a barrier wall. Depending on the site requirements, stabilized clay can be used as such or it can be complemented with manufactured insulation. Mass stabilized clay to be used as a sealing layer material is required to possess good earth construction properties meaning that it should be easy to compact it into a homogenous structure.

A reactive wall is a permeable reactive treatment zone built into the soil which allows for the remediation of the contaminated water passing through it. Mass stabilization mixing unit and pressure feeder are helpful in the construction of reactive walls as they allow introduction of a chemically appropriate material directly into the subgrade.

Mass stabilization has been proven effective in the remediation of contaminated areas and the treatment of contaminated, dredged sediments. Stabilization changes the chemical behaviour of contaminants and encapsulates certain heavy metals into a less soluble and less harmful form. Along with the curing time of the stabilization process, the changing technical properties of the material make it more suitable as filling material from the point of view of earth construction requirements.

a) noise barrier, where the subgrade is reinforced with mass stabilization and the stabilized mass is used as material in the wall embankment

b) vibration reducing structure, where the mass stabilized wall to reduce vibrations is built into the subgrade

c) flood protection dam, where the subgrade is mass stabilized and the embankment's material is a stabilized clay

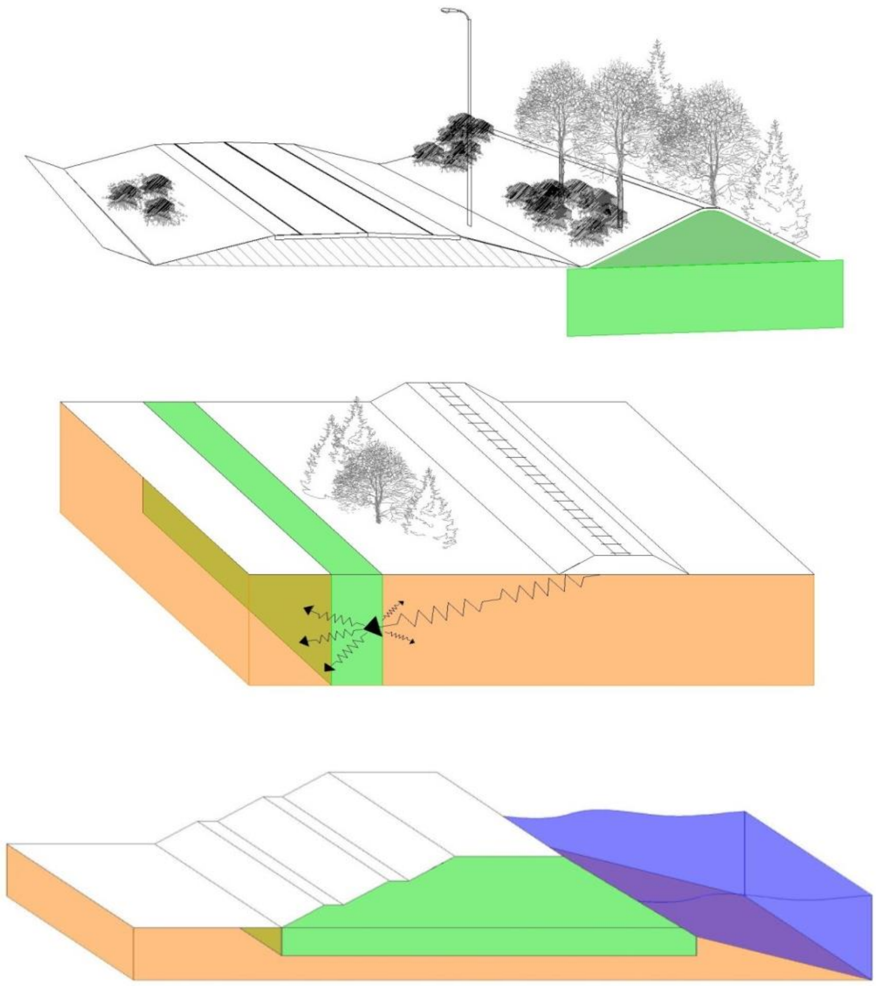
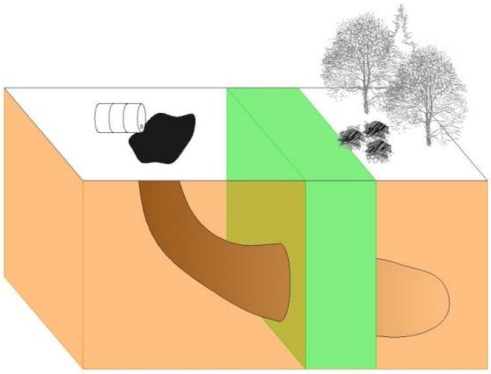
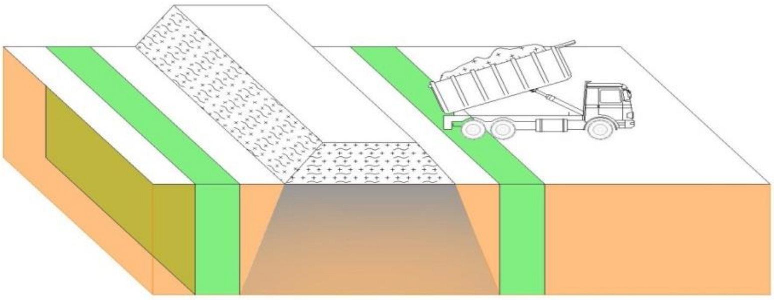


Figure 4.14 Environmental engineering structures. a) Noise barrier, b) vibration reducing structure and c) flood protection dam.

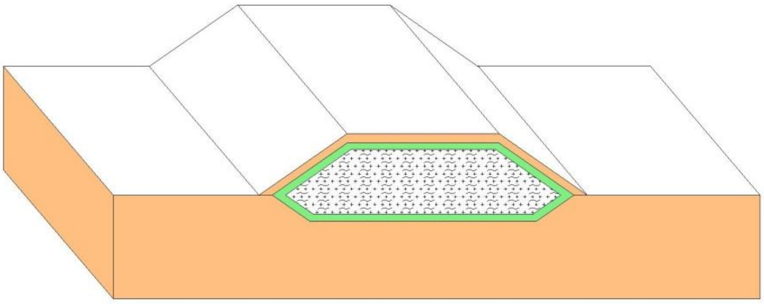
a) reactive wall



b) barrier walls



c) landfill bottom, cover and other barrier structures



d) treatment of contaminated soils and their utilization as filling material in construction of recreation areas

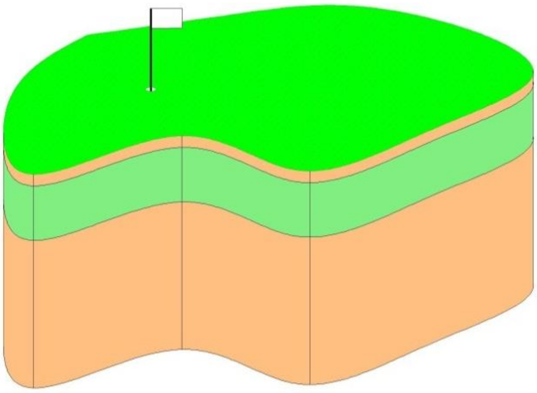


Figure 4.15 Environmental engineering structures. a) reactive wall, b) barrier wall, c) landfill barrier structures and d) treatment of contaminated soils to turn them into a low leaching form.

4.2.2 MINING AREAS

Mining waste management facilities for temporary and permanent storage of overburden and tailings require proper bottom and cover structures, and occasionally reactive walls for the remediation of ground water. These structures can be constructed with the use of mass stabilization. In large mining sites, the choice of the stabilization technology should take into consideration the total scale of the project.

4.2.3 REMEDIATION OF CONTAMINATED SOILS

Stabilization can also be applied as a method of remediation of contaminated soils. The risk posed by the contaminants is lowered by transforming them into a less migrant, less toxic and less soluble form. The first step is to determine the concentration of harmful substances so that a pertinent binder recipe to diminish leaching can be subsequently developed. One of the binder components which has proven suitable to remediation applications is fly ash. Fly ash is a typical by-product of coal burning power plants. Stabilized, contaminated soils can commonly be utilized according to their strength properties as, for instance, a bound bearing structure in construction of various field areas.

From the point of view of immobilizing contaminants, mass stabilization is an appropriate method of treatment of soils polluted with oils, PAHs, and inorganic contaminants such as heavy metals and salts. The treatment sites can be also of a small size. Contaminated soils treatment commonly requires an environmental permit.

Contaminated soils can be stabilized both as an in-situ or ex-situ operation. In on-site remediation, there is no need to remove the soil mass, which substantially minimizes the risk of potential chemical reactions related to excavation works.

Chemical modification is defined as adding such chemical compound to the contaminated soil that will cause a chemical reaction with the harmful substances and transform them into a less soluble form. This means that harmful substances remain in the soils but their harmfulness is immobilized due to a low solubility as, for instance, in the case of oxidation of chromium ions.

Solidification allows transformation of a soft soil mass into a more solid form with the aid of a binder. In case of contaminated soils, adding a binding agent creates a material with a low permeability and "encapsulated" contaminants.

Chemical reactions allow for the degradation of the original contaminants. The reagent may lead to a direct degradation or it can function as a catalyst between the substance present in the material (e.g. water) and the contaminant.

It is essential to pay attention to homogenization of the soil masses during the whole process of contaminated soils treatment. Therefore, the staff involved in the works must be experienced professionals.

4.2.4 TREATMENT OF SULPHATE CLAYS

Sulphate and sulphide rich clay and silt sediments occur in the Ostrobothnian region of western Finland. The sediments date from the Litorina Sea period (currently the Baltic Sea), about 8000- 4000 years ago, when vegetation flourished in the warm climate and the decaying plants caused the eutrophication of sea water. In the anoxic conditions of the seabed bacterial activity resulted in sulphate reduction to sulphide.

As a result of land uplifting process after the glaciation period, the former seabed has risen close to the surface. When close to the surface and above the groundwater, sulphide rich clays are in contact with oxygen and rainwater forming sulphuric acid. Acid generation results in the origin of acidic sulphate soils (pH of 2.5 to 4). Low pH values affect agriculture and forestry by increasing the amount of dissolved heavy metals in the soil. The release of significant amounts of aluminium and other harmful heavy metals into river waters results in fish mortality. Moreover, acidic water causes also corrosion in infrastructure.

Sulphide soils cause a problem particularly when excavated and come in contact with oxygen. There is a reason to suspect that sulphide soil is in question if the colour of clay under the groundwater level is black and it smells of hydrogen sulphide. A clear difference between the black sulphide clay under the groundwater level and the lighter colour layer of sulphate clay above it is visible in Figure 4.16.

a) b)

Figure 4.16. a) Black-coloured sulphide clay deep in the excavation pit and b) black-coloured sulphide clay on the left and oxidized sulphate clay that has changed colour into brown on the right (photo: Jonas Aspholm 2011).

Sulphate soils can be stabilized prior to oxidation by raising their pH value and removing the risk of acidification. According to research carried out in 2011(Lindroos et al., 2012), sulphide clays can be successfully stabilized with mass and column stabilization methods when the soil layer to be treated is located under the groundwater level in anaerobic conditions. After the oxidation, the amount of binder required for the stabilization process of sulphide clays increases significantly.

Stabilized sulphide clays can be used, for example, in the construction of noise barriers or in landscaping projects. The stabilized mass no longer has significant acidification potential. It has been discovered that prior to oxidation of clays, acceptable strengthening results are obtained with binders containing cement, lime, gypsum and fly ash. Fly ash alone allows for the regulation of the pH level of the sulphide clays. However, for the stabilization process the application of fly ash alone is not enough if special strength requirements are set.

Mass stabilization in environmental technology applications

- Noise barriers
- Reactive walls
- Remediation of contaminated soils
- Control of the pH level in sulphide and sulphate clays
- Landfill sealing structures

4.3 COMMERCE AND INDUSTRIAL FIELDS AND STORAGE AREAS

Areas around commercial and industrial spaces often consist of large car parks, storage places and other fields. Mass stabilization has proved to be a feasible method of the subgrade improvement in such large sites. The typical applications include:

- car parks
- yard areas
- industrial fields
- storage areas
- fillings

In the large yard and field areas adjacent to shopping centres and industrial buildings, mass stabilization is applied as a method of settlement reduction and subgrade reinforcement. In house building sites, mass stabilization allows for balancing settlement differences in the yards. Figure 4.17 shows an example of a combined mass and column stabilization carried out in a yard area of a large shop.

There is a possibility to use mass stabilized material as embankment filling and the lower part of the cover layer. In such cases, the material needs to manifest a sufficient bearing capacity and frost resistance.

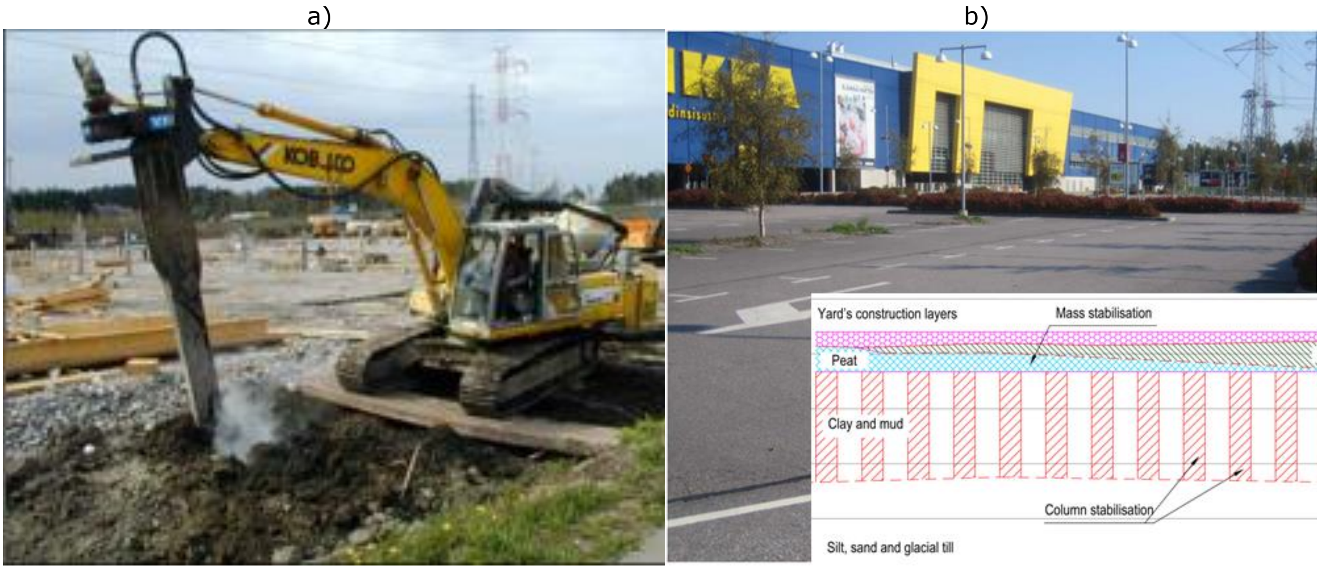


Figure 4.17 Combined mass and column stabilization structure in a yard area of a shopping centre: a) mass stabilization work in progress and b) ready area and scheme of a combined mass and column stabilization structure (photo: Kirsi Koivisto 2004).

5. SITE DEVELOMENT

Mass stabilization is an excellent method to make soft-soil areas fit for construction projects. In such cases pre-construction is a recommended course of action. Prior to the start of construction works, the places where soft soils occur and settlement is not allowed are mass stabilized and preloaded. The pre-constructed and strengthened base allows for subsequent smooth building of streets, pipelines, yard areas, etc. Heavy constructions require column stabilization to be carried out through the mass stabilized layer. Pre-construction with the application of mass stabilization provides a holistic approach towards the challenges arising from the need to handle soft soils in the site development projects. It considerably reduces the costs of operation in comparison to a case where each plot or street section is treated individually and prevents the adverse effects of differential settlement that might appear at the place of convergence of various separate structures.

In addition to the benefits of using mass stabilization as a way of subgrade improvement in the pre-construction stage, there is a variety of other potential applications for this method to be taken into consideration during the site development planning process of a new area. Mass stabilization allows for converting unsuitable soils - originating from the site of concern or other targets - into construction material that can be utilized on- and off-site in various types of fillings, lower bearing courses, noise barriers or landscaping works. The utilization of stabilized soils as material eliminates the need to cart away masses that would otherwise have been considered unfit for the purpose and replaced with imported aggregates. This results in a significantly reduced traffic burden for the public streets and roads network. Also, the need for poor quality soil landfilling is considerably diminished. All these benefits make mass stabilization an eco-efficient and cost-effective solution.

In order to assure that the planning process of a new area is executed in the eco-efficient way that takes into consideration the efficient use of poor quality excavated soils, certain prerequisites need to be met:

- In land use planning or preliminary planning stage, a simultaneous process of designing the soil masses utilization and pre-construction details is initiated. Information required to start this process includes ground investigations and laboratory tests of the samples coming from the soft soils areas.
- Planning and implementation schedule of the pre-construction stage and the utilization of soil masses need to be incorporated into the overall site development project in such a way that all actions are carried out in time. This involves, among others, arranging spaces for the soil masses storage and associated permitting. Also, the potential need for an environmental permit in the case when binding agent in the stabilization process is planned to include by-products should be taken into consideration and handled in time.

Figure 5.1 presents a large size pre-constructed site where the soft subgrade was deep stabilized to create a base course for an industrial courtyard and to serve transportation purposes: a) situation before the execution of mass stabilization; and b) after the mass stabilization). Various possibilities of the application of mass stabilization in a large scale site development project are presented in Table 5.1.

a)

b)

Figure 5.1 Regional site development project where a marshland area treated with mass stabilization becomes fit for construction a) situation before mass stabilization and b) after the execution of mass stabilization (Hautalahti et al. 2007).

Table 5.1 Potential applications for mass stabilization in regional building project.

	Subgrade reinforcement	Construction / filling material	Environmental engineering structures (vibration, noise, groundwater, flood,…)
Plots	+	+	-
Streets	+	+	+
Municipal engineering	+	+	-
Roads	+	+	+
Railways, railway yards	+	-	+
Flood protection	+	+	+
Noise barriers	+	+	+
Ports and fairways	+	+	+
Landfills	+	-	+
Contaminated soils	-	+	+
Landscaping	+	+	-

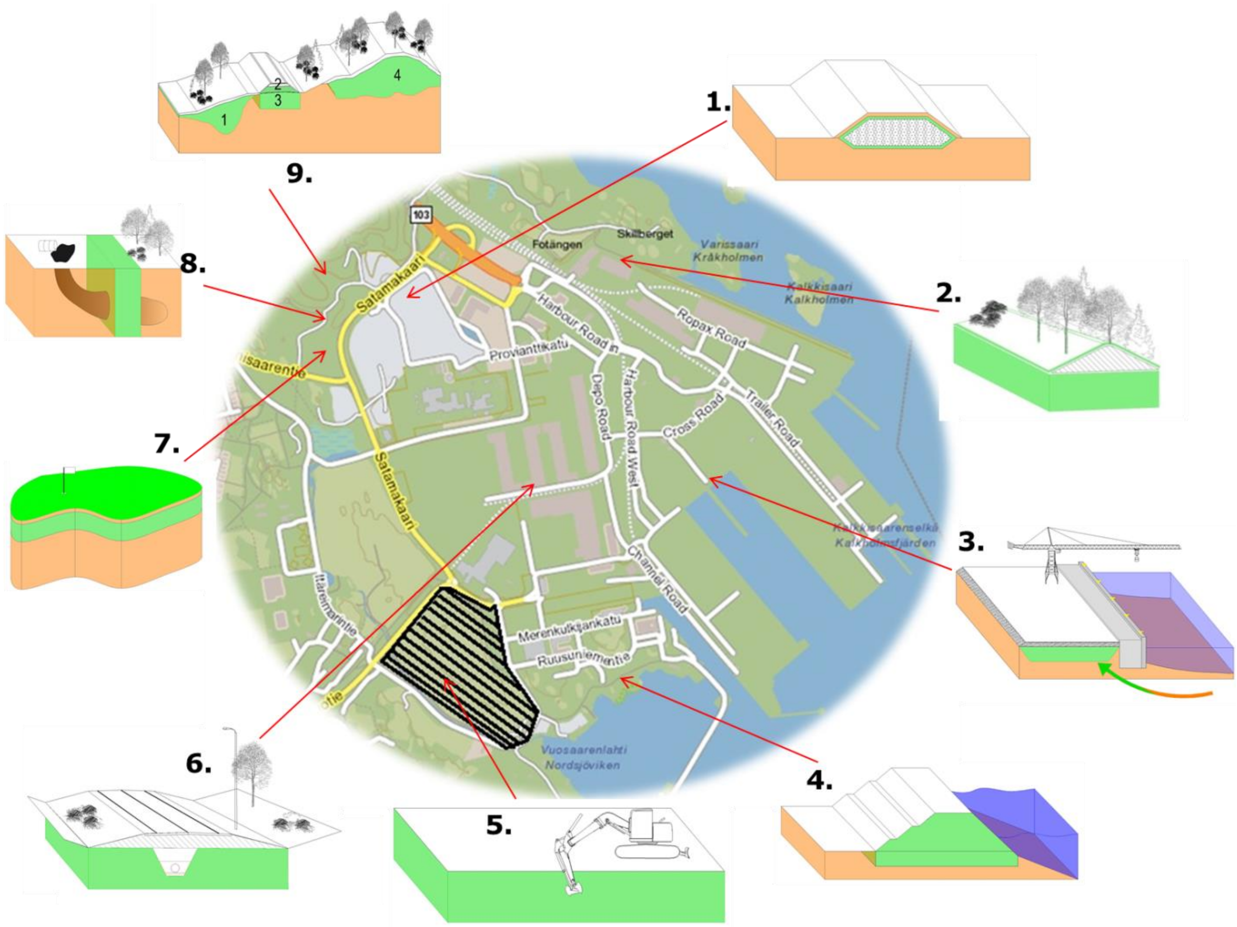


Figure 5.2 Mass stabilization applications in big regional building projects: 1. compaction structures, 2. noise barriers, 3. port structures, 4. flood barriers, 5. pre-construction, 6. road, streets and municipal engineering, 7. utilizing contaminated soils, 8. environmental protection structures and 9. landscaping.

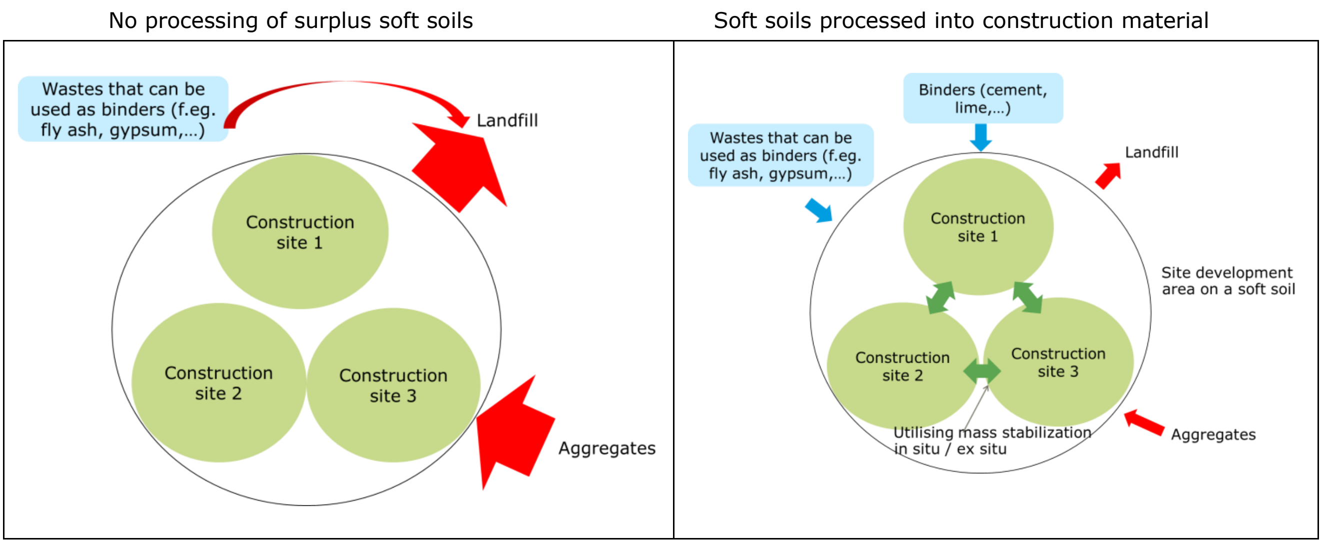


Figure 5.3 Utilizing low-quality surplus soft soils in regional building projects:
a) "Traditional" procedure, where low-quality soils are transported to landfill, and
b) Optimized procedure, where low-quality soils are processed into earth construction material.

Table 5.2. Stages of the planning process and pre-construction planning (based on the table presented in the publication of Nauska & Havukainen, 1998).

Stages of planning	Pre-construction planning
Master plan	- excluding areas not fit for construction purposes - preliminary examination of potential costs associated to various ways of handling soil masses
Component master plan	- preliminary assessment of the need for pre-construction - preliminary calculations of soil mass volumes - minimisation of surplus soil masses and searching for repository - initial design of pre-construction
Urban planning proposal	-determination of the future ground levels and settlement calculations -areal stability calculations -setting settlement criteria -comparison of various options of pre-construction
Urban plan draft	-creation of the pre-construction building plan
Urban plan	-commencement of pre-construction works

6. STAGES OF THE MASS STABILIZATION PROJECT

6.1 PROCESS

The main stages of the mass stabilisation project implementation and its progress can be depicted in the way which is presented in Figure 6.1. In practice, many of the project phases proceed simultaneously and involve interaction.

Prior to the execution of work, versatile initial information shall be collected. This includes data concerning such issues as, the existing soil survey maps and earlier field investigation results. Additionally, it is necessary to find out previous experience of deep mixing works adjacent to the site, including the results of field tests to confirm the design. Based on the available information and on the requirements set by the preliminary plans, complementary ground investigation programme is designed. This involves sounding investigations, sampling, groundwater measurement, laboratory tests, etc. Also, the stabilization test programme is determined at this stage. Provided there is sufficient information available on the previous deep stabilization projects carried out in the area of concern and the results obtained, the new stabilization tests might not be always necessary. In general, any previous experience from the same area or from other sites with similar soil conditions is to be taken into account while planning stabilization tests.

Depending on the size of the site, its complexity, as well as design and implementation schedules, stabilization tests may be carried out either in one or more stages. Samples required for the stabilization tests are usually taken only once regardless of the amount of the laboratory testing stages. If stabilization tests are executed in more than one stage, the aim of the first stage is to find out which binder agents are suitable in a given target, and afterwards the focus is more on the ratio of various components of the binder and the optimization of binder amount.

In order to obtain necessary initial data to perform mass stabilization planning, the following investigations are required:

- defining borders of the soil layers
- determination of index properties of the soil layers; in all cases: the water content and organic matter content (since mass stabilization method is often applied in soils with the high content of organic impurity, the amount of humus and its variations have a significant impact on the stabilization process and the amount of binder required) and upon consideration remoulding index, grain size distribution, and in some cases also the pH, SO_4 and Cl measurements
- identification of strength properties of the soil layers – various measurement methods are possible, i.e., vane shear testing, CPT. Sometimes tests are carried out in the laboratory
- determination of settlement characteristics of the soil layers – usually done with consolidation test (oedometer)

The stabilization characteristics of the soil layers are determined:

- with stabilization tests conducted in the laboratory
- by performing in-situ trial stabilization
- on the basis of experience gained from the previous stabilization projects carried out in the same geological formation.

Geotechnical dimensioning and design are carried out in stages along with the design development and its revising process. The timing of performing stabilization tests during the design process varies. In some targets, on the basis of previous experience or knowledge it is possible to make reasonable assumptions that the planned mass stabilization strength can be achieved. This allows for carrying out the design with the use of target strength values based on experience and performing stabilization tests afterwards. In such a case, stabilization tests might also be included into the responsibilities of the contractor that would determine the binder recipe to be used (quality and quantity) within the process of contract calculations. However, such procedure requires a lot of time during the contract calculation stage. The common practice is to schedule stabilization tests in such a way that the results are available during the design process.

In simple cases, the design process and stabilization tests can be performed simultaneously. Figure 6.2 illustrates how the mass stabilization project stages progress with time. Figure 1.1 presents the parties involved in the project works and Table 1.1 lists the duties of those parties.

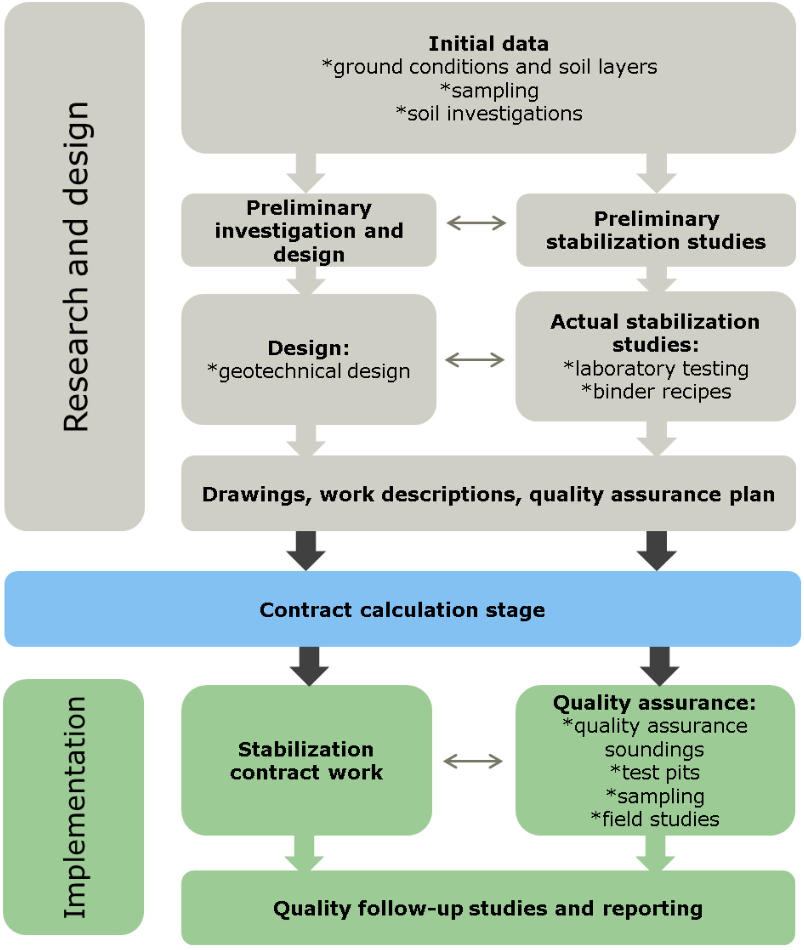


Figure 6.1 The main stages of the mass stabilization project. In some cases, it is possible to progress straight from the preliminary planning stage to the implementation stage. Documented experience of prior deep stabilization carried out in the site or the adjacent area constitutes a prerequisite to such a progress.

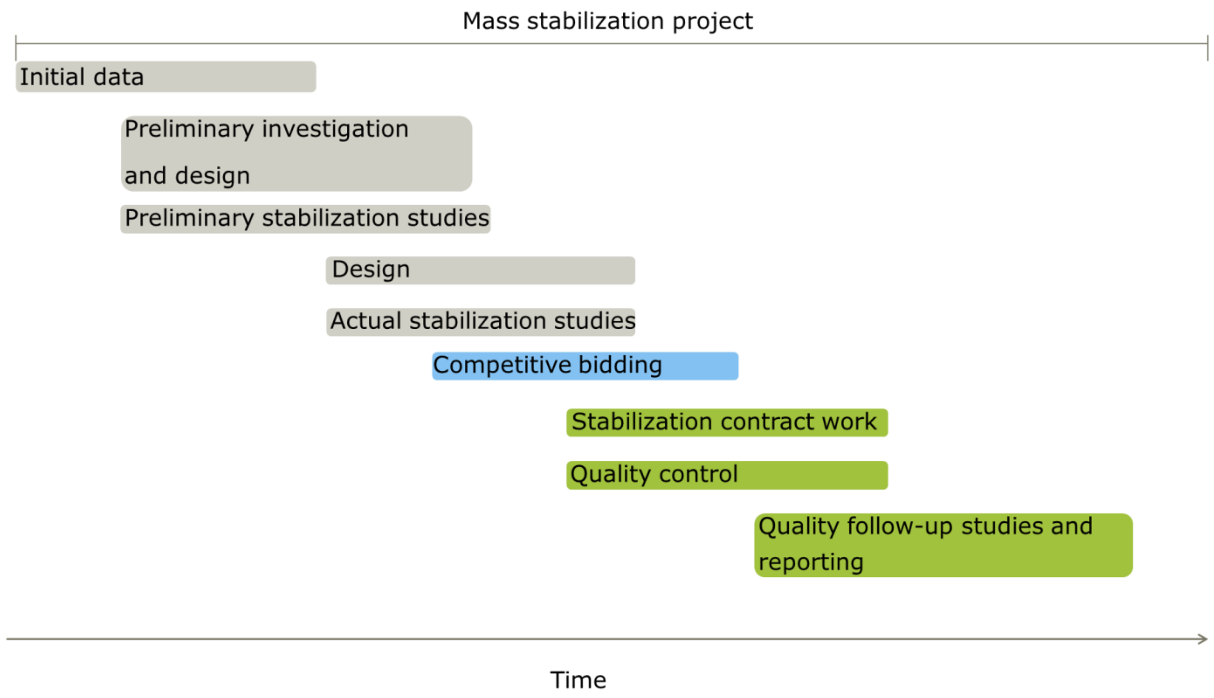


Figure 6.2 The principle of placing mass stabilization project tasks on the time axis.

6.2 INITIAL INFORMATION AND FIELD INVESTIGATION

Mass stabilization project design starts with the compilation of existing field surveying data and other information concerning the site. This provides a basis to carry out the first techno-economic feasibility assessment of the stabilization method in a given site. Providing that the result of the assessment is positive indicating that mass stabilization is the appropriate solution in the target in question, the next step is to plan the complementary investigations bearing in mind the specific characteristics of the method. The aims of the planned studies is to find out the following issues:

- thickness of various soft soil layers, ground water level and its variations
- geotechnical properties of various soil layers; in case of contaminated soils – their environmental properties
- existing structures in use on the site (i.e., pipe lines, cables, overhead lines)
- abandoned and decommissioned structures (previous foundation structures i.e., piles, timbering)
- the need and location of the working areas and communication tracks for the machinery and binder transportation
- the availability of binder agents

In this stage, also samples required for executing stabilization tests are collected.

Ground survey is an investigation method for soils and bedrock that allows for the identification of the structure and properties of the subgrade in the area of concern. The survey is required in the process of geotechnical design and its scope depends on the quality of the subgrade, and the requirements set by the planned load and structures to be constructed. The investigation of soil conditions at the site includes visual inspection, test pit(s), as well as various test borings. Visual inspection results, geological maps and aerial photographs enable drawing conclusions on the soil formations and their structure.

Test pit is the most reliable way to obtain information on the soil strata close to the surface. It allows for making observations concerning soil types encountered in various layers, the presence of cobbles and boulders, soil excavation properties, the stability of the pit wall, groundwater level, and bedrock contact. In the pit, also samples can be taken for laboratory evaluation.

The main purpose of test boring is to observe the resistance met by penetration sampler as boring progresses, especially as differing soil strata are encountered. Based on the resistance variation, test borings can return information on each layer, such as soil density, strength and bearing capacity. Samples extracted from the boring are examined in the field and frequently also taken for laboratory testing.

6.3 PRELIMINARY INVESTIGATIONS AND DESIGN

In the preliminary investigation stage, the technical possibilities of applying the mass stabilization method are assessed on the basis of the initial results of the stabilization tests. The aim is also to estimate the economic factors such as the efficiency and competitiveness of the solution. In this stage, the tests are carried out in such a way that allows for the initial determination of the required binder types and quantities (Phase 1).

Investigations results are used for initial planning of the technical solutions and the adoption of a preliminary cost estimate. They also allow for the determination of the actual stabilization testing programme (Phase 2), as well as for the choice of structure types and/or applications for the purposes of the geotechnical design.

In the cases where there is no previous knowledge about the stabilization properties of soils in the area of concern and there is no possibility to make necessary assumptions on the basis of existing information, the results of the preliminary stabilization tests have to be available prior to the start of first steps of the mass stabilization planning. The same applies if it is suspected that potential contamination of the ground might have an adverse effect on the results of the stabilization process. In most cases, the subgrade can be reinforced with the application of mass stabilization. However, there are also some sites where the subgrade or one of its critical layers cannot be stabilized with the use of an economically feasible binder. In such event, it is not worth to develop a design that would be based on the application of the mass stabilization method.

6.4 DESIGN PROCESS AND STABILIZATION TESTS

In Phase 2 of the stabilization tests, the aim is to find out how the potential binders components, as well as their ratio and amount in the binder mixture affect the following aspects of the stabilization process:

- compression strength to be reached
- necessary hardening time
- compression occurring during hardening time
- susceptibility to changes of the hardening process due to alterations in the properties of the stabilized material, i.e., the impact of changes in water content (for instance, this is important in stabilization of dredged masses that are temporarily stored in basins).

It is typical to mix successive soil layers with each other during the mass stabilization process. For example, an upper peat layer is mixed with the lower layer of clay, silt or sand (or with the upper part of this layer) so that mineral soil is added to peat thus improving its stabilization properties. For this reason, while preparing aggregate sample for the needs of stabilization tests it is reasonable to mix soils from the overlapping layers. It is also possible to improve the stabilization properties of peat or gyttja by spreading sand or stone dust on top of the stabilized layer and mixing it with the stabilized soil material.

Other issues that can be studied include, for instance, the impacts exerted by the hardening temperature, the magnitude of the preload, and the amount of aggregate mixture on the strength achieved. In case of a particularly large or challenging target, or a target where it is easy to launch stabilization works, it is worth executing mass stabilization pilot works which enable in-situ testing of the subgrade stabilization properties and allow for assessing the required binder quantity.

The geotechnical design includes geotechnical dimensioning (i.e., settlement and stability calculations), design of the structures, technical drawings, quantity surveying, work specifications and a quality assurance plan. The design of mass stabilization may also include such issues as binder logistics, temporary storage of binder, and mixing work planning.

Geotechnical design sets target strength for stabilization or the target strength is determined on the basis of the stabilization tests results taking into consideration techno-economic aspects. The target shear strength in mass stabilization generally varies between 30…70 kPa, being rarely more than 100 kPa.

Mass stabilization work specifications define work instructions and operating procedures, set technical requirements for the stabilized material and define technical quality assurance plan taking into consideration the specific conditions in the site of concern– i.e., the type of the material to be stabilized and variations in its quality, binder agents, the overall time available for the hardening process, time of the year. Depending on the client needs and the type of site in question, mass stabilization work specifications as a whole can be tailored to the site specific requirements, or they can be based largely on the general work specifications and quality requirements including only some parts focusing on mass stabilization.

The aim of the detailed instructions is to minimize risks during construction time and to ensure high quality implementation of work according to the plans. One of the examples is the proper storage of reactive binders that strictly complies with the rules.

The quality assurance plan sets out the measures during the construction time and for the quality control follow-up period. In addition, the plan includes carrying out surveillance soundings typically 1...3 months after construction, and other potential follow-up measurements.

6.5 COST CALCULATIONS

When drawings, work specification and other required documents are ready (or ready enough) it is time to launch competitive bidding. Provided that the implementation of mass stabilization is set by the negotiating procurement or mass stabilization is a part of a larger contract as an alternative solution chosen by the contractor, there is not necessarily a need to arrange completive bidding. It is also possible to carry out mass stabilization works as part of a framework agreement, in which case no contract competition is required if the works are to be carried out within the framework contract period.

At this stage, the price of the mass stabilization works is set and the contract is prepared. This is also the last moment to decide who is responsible for the subgrade stabilized the with the chosen binder – in practice, the binder recipe functionality lies within the responsibilities of either the property developer or the contractor depending on which of two has determined and priced the binder recipe to be applied.

6.6 STABILIZATION WORKS

Mass stabilization is carried out according to plan. If necessary, the plan is updated or complemented along with the progress of works. Mass stabilization requires a target specific site organization plan which describes how the contractor should implement mass stabilization works towards high standards and how to arrange quality control which lies within the contractor's responsibilities. The site organization plan is based on work specifications but the contractor can supplement the work specifications with such issues as, for instance, the contractor's own quality control actions.

The contractor's own quality control takes place simultaneously with the progress of mass stabilization works. In practice, this means the surveillance and follow-up actions concerning such issues as: the quality of the masses to be stabilized (e.g. water content), conditions encountered in the site (and how they correspond to the conditions described in the plans), the quality/quality fluctuations of the stabilized masses, the amount of binder, the progress of hardening process, as well as the homogeneity and compression strength of the final product.

It is recommended to employ an external quality controller for the duration of the implementation works. In such case, the work of the external quality controller starts before the launch of the project – quality control of the implementation process. If the role of the external quality controller is to state the quality of the stabilization works outcome – in this case, this would include the quality control soundings or compression tests of the samples – it is not the responsibility of the external quality controller to carry out the work quality guidance tasks and the quality controller job starts only weeks / months after the launch of stabilization.

In the case mass stabilization is planned to be applied in large, particularly demanding sites or in a site with an unfamiliar soil type, it is recommended to carry out trial stabilization prior to the start of the actual stabilization works. This allows to test the technical aspects of the implementation, the quality of the final result, and work capacity issues, as well as to optimize the binder recipe. In order to avoid mobilization of the machinery only for the purpose of the trial stabilization, the actual stabilization project can start with some initial works carried out in the test areas where it is possible to try different binder amounts or mixing works variations. While waiting for the quality control results of the trial areas, the stabilization works can be performed with the amount of binder seen to be sufficient based on the available knowledge.

Stabilization works and quality control consist of the following tasks:

- construction
    - organization of works and marking the area
    - when needed cultivation and homogenization of the material to be stabilized
    - actual stabilization work, quality control and guidance
    - quick tests to be carried out during the work (e.g. binder amount)
- quality control
    - investigation of samples
    - column penetrometer and vane penetrometer for columns
    - other necessary soundings or investigations

6.7 CONSIDERATIONS RELATED TO WORK PROGRESS AND THE FINAL RESULT. OTHER ISSUES TO BE TAKEN INTO CONSIDERATION

The progress of the mass stabilization works and the quality of the outcome are affected by various factors. At least the issues stated below should be taken into account while planning and conducting the work:

- quality of the soil masses to be stabilized (geotechnical and chemical properties)
- variations in the quality of the masses
- cobbles, tree stumps, roots, logs, and other objects in the soft soil that can delay work
- obstacles and structures below the ground and above the surface, protecting and avoiding to damage the structures that need to be preserved
- time of the year and temperatures (winter conditions)
- flood water, drainage, etc.
- binder availability and its storage options; special instructions concerning binder storage
- binder dusting, prevention of dusting, sensitivity of the surrounding environment to binder dust
- transportation of the machinery and binder to the site
- storage areas
- susceptibility of the surrounding environment to potential failures, displacements or vibrations
- working time limitations concerning time of the day, day of the week, or time of the year (e.g. bird nesting season)
- quality requirements concerning the final structure and how demanding their achievement is

- impact of the initial hardening on the progress of work implementation (how quickly it is possible to install the seal course or when is it possible to drive the machinery on top of the stabilized layer)
- project schedule in relation to the time necessary to complete the works

Stages of mass stabilization project

- Collecting initial information and data
- Initial investigations and design including initial stabilization tests
- Dimensioning and actual stabilization tests
- Design, technical drawings, work specifications, quality assurance plan
- Competitive bidding
- Stabilization works and quality control
- Follow-up quality control and reporting

7. MASS STABILIZATION BINDERS

7.1 GENERAL

The most commonly used binder in mass stabilization is cement but the use of lime is also possible in many cases (lime cement). Additionally, various reactive by-products originating from industrial processes may be used alongside as a mixture component. These include such by-products as slags, fly ash, and/or gypsum components. The use of industrial by-products allows for achieving stabilized masses with a better technical and/or environmental quality, as well as it decreases the overall costs of the binder agents.

The main factors influencing the selection process are target strength, material price and its availability. Other issues to be considered include, among others, curing time, stress-strain properties, and in some cases also impacts on leaching and permeability features. It is also necessary to take into account such characteristics of the machinery to be used as, the maximum binder feeding capacity and the number of the binder subcomponents. It is also important whether dry binder is fed or it possible to use moistened binding agent, as for instance, stockpile fly ash.

7.2 CEMENTS

Cement is the most commonly used binder type in mass stabilization. The advantage of using cement in comparison to other binders is that it allows for fast initial curing of the stabilized mass (strength development), which in many cases positively affects the progress of work. The long-term curing features of cement are usually smaller than in case of other binders. When cement is used, a hard but relatively brittle structure is a typical result, which in the case of mass stabilization does not constitute a problem when the final structure is a thick slab-like and coherent mass layer.

In cement, the movement of calcium ions (diffusion) in the aggregate material is low. Therefore, if only cement is mixed as binder with the aggregate material, the potential non-homogenous result will not improve with time. For this reason, in the case of cement, the quality of mixing work is more strongly evident in the final structure than in the event when calcareous binders are used.

In accordance with the EN 197- standard, the cement products used in mass stabilization are as follows: composite Portland cement with normal initial strength (CEM II / BM (S-LL *) 42.5 N), Portland cement with limestone with high early strength (CEM II / A-LL 42,5 R), Portland cement with high initial strength (CEM I 52.5 R), and SR-cement (CEM I 42,5 n-SR3). For the needs of stabilization of soils with the high content of sulphates, the SR-cement is the most suitable solution as this type of cement is resistant to sulphates.

7.3 LIME PRODUCTS

For stabilization purposes, lime is mainly used in the form of quick lime (CaO) and sometimes also in the form of hydrated lime ($Ca(OH)_2$). In practice, almost always lime products are used as a mixture with other binder components, in most cases with cement.

Quick lime is a very reactive binding agent. It binds water very efficiently and this reaction releases heat which accelerates the subsequent curing reactions. When lime is used, the obtained stabilized structure becomes more coarse and its water permeability might increase. The initial curing effect is relatively slow but on the other hand, long term reactions occur in the structure to a significant extent. Lime is indeed a slowly stabilizing binder which pozzolanic reactions may continue for years after completion of stabilization work. The ability of lime to diffuse into surrounding clay allows to compensate for the non-homogenous result of mechanical mixing and through this to improve the quality of the final structure.

7.4 OTHER BINDING AGENTS

Other binders commonly utilized in mass stabilization include by-products of industrial processes, such as various slags, fly ashes, and gypsum products. In most cases, these materials are used together with commercial binder components with the objective to improve the technical and environmental properties of the final structure, and also in order to decrease binder costs. In some special cases, it is possible to carry out stabilization/solidification of soil masses only with the use of by-products as binder components.

The use of the so called by-product binder components commonly increases to some extent the overall amount of binder, but on the other hand it also allows for significant cost savings. The economic advantage makes the mass stabilization method more attractive and competitive. The drawback of the increased amount of binder lies in the fact that it may slightly slow down the actual execution of stabilization work.

There are several issues that need to be taken into consideration while using slags, fly ashes or gypsum products as binder components including the following:

- availability of the material, its quality and variations in quality
- temporary storage needs
- ways of processing and transporting the material at the construction site
- possibilities to feed simultaneously two or more binder components; potential need to mix binder components already prior to the start of actual stabilization work
- preservability of binder components or binder components mixed beforehand
- mass stabilization equipment allows for feeding of only dry and fine-grained binder components; wet binder components need to be spread on top of the layer to be stabilized and if necessary, they need to be premixed with excavator
- potential negative impacts of the binder agents on the feeding equipment
- permitting issues associated to the use of secondary materials

The possibility to reach the required properties with the use of alternative binder solutions, as well as the factors that affect the final result need to be sorted out beforehand in the laboratory.

Combining various binder components allows to create such tailored mixtures that in a given target site enable achieving the required properties to a great extent. Alterations in binder recipe affect the strength development speed (fast development is not always desirable), consolidation of wet masses (components that bind water), the final strength of the structure, deformation properties, the potential to compensate for uneven mixing of binder with soil, the potential to bind harmful particles in stabilized soil, water permeability and naturally also the costs of binder. In most cases, cement or lime are part of the mixture in the role of a catalyst triggering the reaction.

7.5 STABILIZATION TESTS

The objective of the stabilization test programme is to establish some competitive solutions is terms of technical performance and economics, which will in turn allow to select the final solution best fitting the requirements of a given site. In some cases, i.e. contaminated soils, also environmental suitability properties affect the choice. The aim of the investigation is to confirm the quality properties of the end result, to choose the best binder recipe and to optimize the amount of binder, as well as to determine the factors that have an impact on the final structure and the scope of their impact.

The determination of the material properties to be achieved through stabilization process is carried out with such an accuracy that allows for a reliable implementation of the 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.

Stabilization tests are often carried out in phases and they start with screening the performance of different types of binders, the properties they allow to achieve, and in particular, the differences among various alternatives. Based on the results obtained, a few most promising solutions are selected for further detailed investigation. Detailed studies result in the optimization of the binder components ratio in the mixture and the optimization of the binder amount, as well as in the better understanding of the aggregate material variations in the target site and the identification of some factors critical for the outcome, such as challenging areas/layers or troublesome components. The aim is also to find out the ways to address these challenges that would allow for the best end result – the use of auxiliary aggregate material, local changes in binder type, etc. Other types of tests that are commonly carried out in this stage include establishing the differences among binders options concerning hardening time, the influence of temperature on the curing process. In some cases, it also required to perform some additional test, such as for instance, a triaxial compression test.

7.6 BINDER RECIPE DETERMINATION

Binder costs commonly constitute about 50-70% of the total budget of mass stabilization. Therefore, the optimization of binder type and its amount substantially affect the implementation costs. It is important to identify the needs and requirements of the target site in relation to the binder but on the other hand, binder overdosing should be avoided. In some cases, the sufficient initial curing process is the precondition of smooth implementation of works allowing for fast introduction of a target site. In other cases, rapid initial curing might be disadvantageous, for instance when stabilized masses are transported and finally compacted in the utilization target only after the initial curing phase. Again, in some other targets, the strength development speed is of little practical significance, in which case there is no need to invest into fast initial hardening. Since construction project schedule is one of the most important factors influencing the process of decision making, the issues mentioned above should be taken into account already in the process of binder recipe creation.

The outcome of the construction process should be of a uniform quality and the quality level to be achieved in the planned structure is determined in practice by its weakest point. If the entire target is dimensioned according to the properties of aggregate which is most challenging, it leads to the situation where the amount of binder planned to be used in substantial parts of the site is too high, thus resulting in unnecessarily increased costs. On the other hand, if design is based on the average quality of the soil material this can result in the situation where in the challenging places or layers, there will remain poorly stabilized points. Therefore, it is important establish the critical factors affecting curing and determine the most challenging areas or layers in order to be able to tailor the binder recipe according to the specific needs of a given area. In this way, it is possible both to avoid binder overdosing and to ensure that quality standards are met throughout the whole target site.

In the process of binder recipe creation, the attempt is to take into account both technical and economic issues. This means that apart from the optimization of the quality and quantity of binder, the possibility to use alternative components is assessed. In many cases, it is possible to reduce the cost of binder by replacing part of the commercial components with industrial by-product materials.

The importance of binder recipe becomes more significant if the conditions differ from the ones typical of normal stabilization process. For instance, it should be attempted to assess the potential impact of very hot or cold temperatures on the behaviour of treated masses during stabilization work, as well as the effect on the end result in order to avoid possible delays due to slower initial curing and associated problems with regard to the progress of works.

Similarly, it is worth to determine the ways of addressing challenges set by some targets which are more demanding than usually. This could be, for instance, handling very dry masses which is possible with the addition of water. It is also important to assess the impact of the potential deviations occurring during the implementation stage on the quality of the final structure and to set borders to stick to in order to achieve the desired quality.

Binders in mass stabilization

- Binder costs constitute a considerable part of mass stabilization project
- Cement, lime or their mixtures are the most commonly used binders
- In some sites, various slags, fly ashes and gypsum materials can be considered as binder components
- Binder selection is influenced by such factors as, curing and deformation properties, leaching and permeability characteristics, as well as the speed of initial curing and the overall curing process
- Utilizing industrial by-products as binders allows for economical treatment of large masses of soil

7.7 LABORATORY TEST METHODS

Laboratory tests used

For the purpose of evaluating quality and quality variation of the aggregate material (classification), the following material properties are commonly investigated and determined in the laboratory:

- water content (oven drying), (%)
- wet density, (kg/m^3)
- loss on ignition (annealing oven, 800 °C), (%)
- granularity (aerometer test, if necessary, wet sieving)
- pH
- SO_4- ja Cl-content

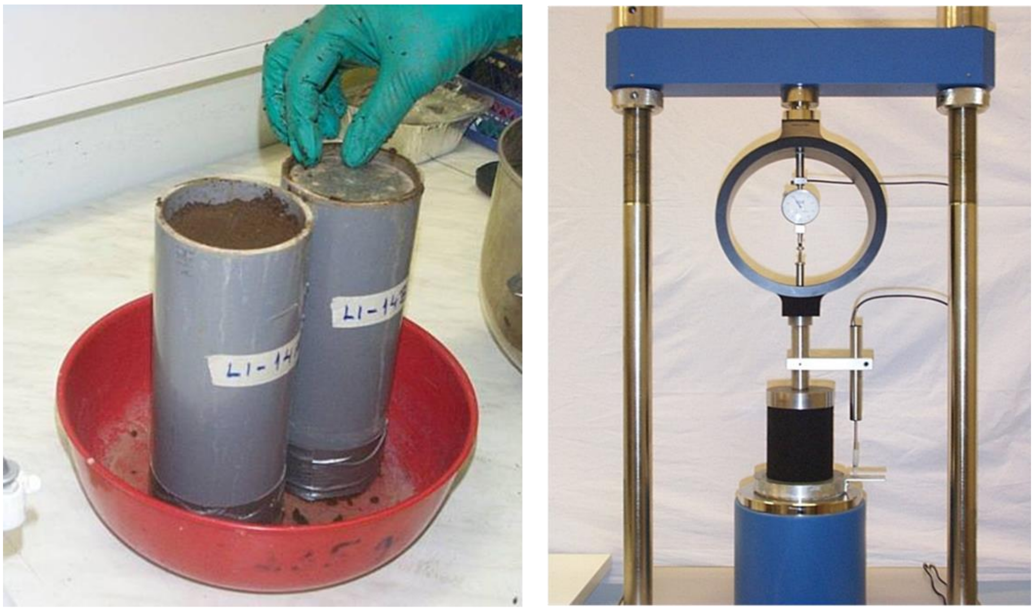
On the basis of drilling and laboratory tests results, it is attempted to initially outline the quality of the soil masses to be stabilized including variations of quality in the target site, as in particular to evaluate the stabilization potential bearing in mind the target's most challenging areas and/or layers. For the purpose of the actual stabilization tests, aggregate samples are chosen in such a way that the quality is representative for the entire site as much as possible. This concerns both various areas of the site and the potential differences in strength development potential identified with the classification tests. The data obtained as a result of all the tests mentioned above allows to plan the actual stabilization process so that it serves well the needs of the entire site.

For the needs of the stabilization tests, strength properties of masses are most commonly determined with unconfined compression tests which if necessary are supplemented with triaxial compression and consolidation tests (oedometer). Environmental properties tests are often supplemented with the measurement of water permeability and determination of leaching behaviour.

In stabilization studies, it is important to take into account the quality of the tested aggregate material and choose the suitable manner of executing strength tests. In the case of clays, silts, and dredged sediments, the most commonly applied method includes mixing the tested binder with aggregate material, compacting the obtained mixture into sample cylinders, protecting the cylinders from drying, and storing them in standardized temperature during the curing time. Preloading is not applied in the process of testing these materials, unlike in the case of peat.

After mixing binder with peat, sample cylinders are set in the preload bench, where the stabilized mass is subjected to vertical load (commonly 18 kPa). Due to vertical load, the stabilized mass settles to a considerable degree during the curing time, especially during its initial stage. As a result of compression, the mass becomes compacted and water is removed. The impact of preload on the targeted strength is significant and according to experience, the achieved strengths correspond remarkably better to the real life results obtained in the site than if preloading is not applied. The studies give also an indication on the expected magnitude of the peat layer compression. Applying different levels of preload during testing time allows, if necessary, for assessing also the possibilities of influencing strength development or settlement behaviour in the stabilized area with the use of additional load or loading berm.

In case of gyttja and other relatively highly compressible materials, both of the testing methods mentioned above can be used depending on the situation. The test method is selected on a case-by-case basis, so that the chosen method corresponds as closely as possible to the actual situation in the area of stabilization in respect to such issues as the expected compression of the layers, load on the stabilized layers, as well as factors that have a compressing effect (e.g. preloading or overloading berm) and issues concerning water removal from the structure.



a) b)

Figure 7.1 a) Peat specimen making in the laboratory and b) unconfined compression test is commonly used to measure strength

8. MASS STABILIZATION DESIGNING

8.1 INITIAL DATA

The amount of initial data required for mass stabilization designing varies depending on the complexity of the target. For example, the amount of the ground survey data can be smaller if there is a clear-cut boundary between the stabilized layer and the next layer, than in case when mass stabilization is carried out to a certain depth and settling layers of soils are left below the stabilized stratum.

The first preliminary assessment of whether mass stabilization is a suitable solution in a given target can usually be done with quite incomplete initial data if there exists previous experience of deep stabilization in the area of concern. The more "unknown" the ground conditions in the area of concern, the more initial information is required for the needs of techno-economic assessment. If there is no previous experience of the stabilization potential of a given material and no stabilization tests results are available, making a reliable preliminary estimate is not possible.

In general, prior to the start of designing mass stabilization, the following data concerning target site needs to be gathered:

- Borders of soil layers
- Index properties of soil layers (grain size distribution, water content, organic matter content)
- Special investigations of soil layers (e.g., pH level, SO_4– and/or Cl content, contamination, …)
- Strength properties of soil layers
- Settlement properties of soil layers
- Ground water and perched water level and its range
- Existing structures

Mass stabilization design starts with planning additional ground investigations. Sounding results and information on samples obtained during complementary investigations constitute a basis for programming stabilization studies and carrying out geotechnical design. Mass stabilization design includes the following elements:

- Complementary studies programme
  - Soundings and sampling, mapping, etc.
- Stabilization tests
  - Binder mixture (quality and quantity)
  - Shear and compression strength
  - Settlement during possible preloading time
  - Bearing capacity (modulus)
- Geotechnical design: subtasks
  - Stability review
  - Settlement calculations
  - Stability of excavations and trenches
  - Carrying out capacity design
  - Determination of depth of soil freezing and frost heave
  - Other
- Drawings
  - General site layout

- Longitudinal and cross profiles
- Detailed drawings (if necessary)

- Quality requirements and work specifications
  - Binder quality requirements, binder amount, tolerances
  - Requirements for stabilization mixing work
  - Stabilization strength requirements and tolerances
- Design during stabilization process
  - Design to be carried out during stabilization process and afterwards

8.2 DETERMINATION OF DIMENSIONING PARAMETERS

The dimensioning parameters of mass stabilized soil layers can be determined either with the laboratory tests, with trial stabilization carried out in the site or based on the information of previous stabilization works carried out in the same area and ground. If information on mass stabilization performed in the vicinity of the target site is utilized in the design, it is necessary to check soil properties separately. At a minimum, the correspondence of organic matter and water content in both sites must be investigated.

Programming of laboratory tests and field trial stabilization starts with setting priority of the matters to be investigated and deciding on the number of alternative solutions. This includes:

- Choice of binder / binder mixture
- Binder amount
- Details of work technical procedures
- Curing time

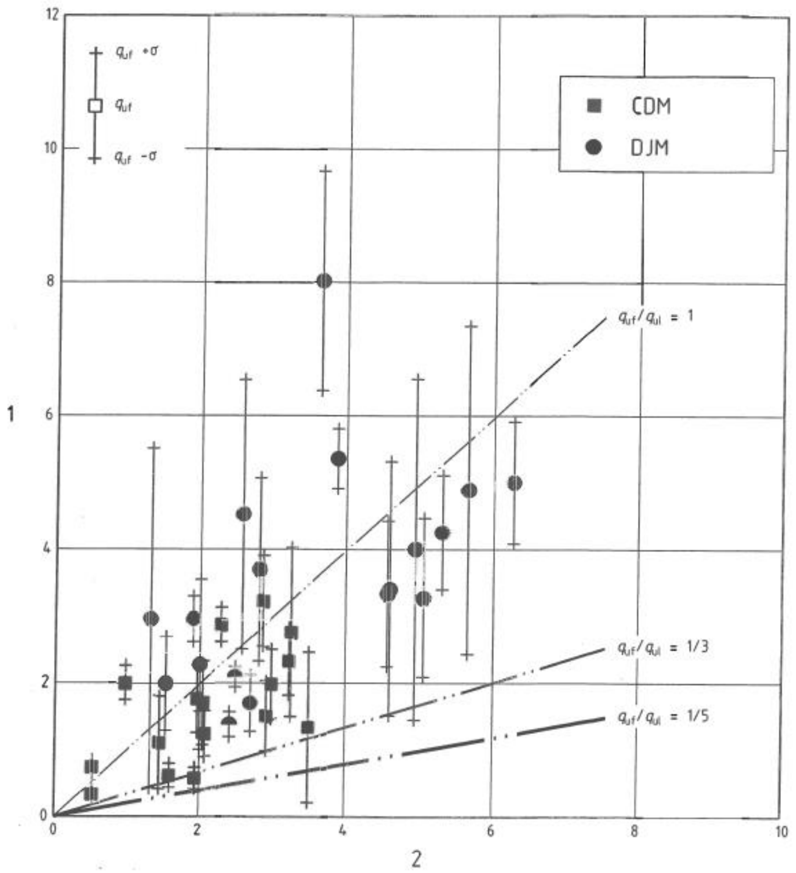
Specimens made in the laboratory always allow to determine at least compressive strength and deformation modulus E (E_{50}) with unconfined compression test. In case of demanding sites, it is recommended to determine strength and deformation parameters of the stabilized soil with triaxial compression tests, which allow for tracing prevalent load condition in the ground and occurring deformations better than the unconfined compression test.

The un-homogeneity is typical of mass stabilized soil material. Therefore, during trial stabilization it is necessary to carry out a sufficient number of quality control tests. In order to determine shear strength, at least from 8 to 10 representative penetration tests (e.g. column penetrometer) should be performed and from 4 to 6 vane shear tests (e.g. column vane test) should be carried out per binder combination.

The indicative shear strength of the mass stabilized soil can be estimated already in the stabilization tests planning stage. The choice of binders to be tested and their amount is done on the basis of previous experience. It depends on the preliminary strength target and the index properties of the soil layers (grain size distribution, water content, organic matter content, sulphur content).

The strength of a laboratory-made stabilized test sample is usually higher than the strength of a corresponding material from the field. The difference is mainly due to a more efficient mixing of the binder and soil in the laboratory. Also the prevailing temperature in a laboratory is more even and differs from the temperature in the field conditions. The former is apparent when comparing the strength of well mixed laboratory test samples with the strength of samples from similar but less homogeneously mixed in situ mass stabilization. In laboratory test samples, the attainable strength is usually from 10 to 50 times higher than the strength of the natural (not stabilized) soil (EuroSoilStab 2002). In in situ mass stabilization, the attainable strength is normally from 20% to 100% of the strength of the laboratory test pieces. The correlation between laboratory test specimen and field samples is usually better at lower strength levels and as the lime content of binder is increasing.

The shear strength values obtained in the laboratory need to be multiplied by the correction factor q_{uf} / q_{ul} defined, for example, in the EN 14679 standard (Figure 8.1). However, the graph does not present strengths typical of mass stabilization (< 100 kPa). It has been observed in practice that for cement binders the correction factor can be significantly less than 1 if water content of the soil mass is high and binder amount is low.



Key

1. Field strength q_{uf}, MPa

2. Laboratory strength q_{ul}, MPa

Figure 8.1 Relation between strength results of field and laboratory tests for deep stabilization. (EN 14679: 2005+AC:2006)

8.3 OVERALL STABILITY

Design procedure:

Safety against failure of a mass stabilized structure is determined by using the procedure either set by the client or agreed upon with the client. In Europe, it is ruled by the Eurocode system or the national procedure set by national Codes of Practice. The requirements for the serviceability and ultimate limit states are to be specified by the client. In designing according to the calculation rules set by the Eurocode, the selection of design situations, actions, approaches, etc., has to follow the principles specified in a national annex.

In section 5.5 "Ground Improvement and Reinforcement" of the current EN 1997 standard there is a short section concerning soil improvement which will be rewritten in the next Eurocode version. Section 5.1 includes a statement that *"Ground, which is treated to improve its properties may be either natural ground or fill. Design procedures for geotechnical works that include the use of improvement shall be those presented in Sections 6 to 12"*. (6. Spread foundations, 7. Pile foundations, 8. Anchorages, 9. Retaining structures, 10. Hydraulic failure, 11. Overall stability and 12. Embankments). In practice, design procedures concerning "Overall stability" and "Embankments" are mostly needed in designing process of mass stabilized structures.

Execution standards for ground improvement processes are set by the CEN TC 288 (Execution of special geotechnical works). At present, the available execution standard for mass stabilization is "EN 14679: Deep Mixing" which covers some aspects of design (Annex B). However, these aspects apply to column stabilization and only some principles are suitable for mass stabilization.

The EuroSoilStab Design Guide (Soft Sol Stabilisation CT97-0351, 2002) presents a design procedure for column and mass stabilization. This procedure is based on the preliminary version of Eurocode 7 (ENV 1997-1) and is not in accordance with the current EN 1997. In the ESS Design Guide, mass stabilization is designed in such a manner so that the stabilized structure and its close surroundings gain satisfactory overall stability eliminating the risk of failure due to large deformations.

Stability calculation:

In stability calculation, mass stabilized soil is assumed to be a homogenous, elasto-plastic soil layer. The uncertainties of the result of mixing and homogenization of the stabilized soil must be taken into consideration in the design (Figure 8.3).

The starting point of stability analysis is testing the stability of not stabilized soil structure and afterwards, testing with taking stabilization into consideration. The baseline situation calculation (no stabilization) allows to assess to what extent stability plays a significant role in stabilization dimensioning.

The stability of a mass stabilized structure is determined with the use of circular failure surfaces, apart from the structures in which according to design, a weak and/or oblique non-stabilized layer will remain under the stabilized stratum. In such cases, it is recommended to apply also a combination of sliding surfaces in the calculations of stability.

If a sloping surface or a structure with a lateral load are in question, it is necessary also to assess the quality of contact between the stabilized layer and the underlying non-cohesive soil, i.e., is it possible that there remains a plane of weakness in the boundary surface or is it possible that the mass stabilized layer reaches the surface of the non-cohesive zone. In most events, it is safe to assume that the contact of the mass stabilized and underlying non-cohesive soil layers is not perfect.

If a narrow and heavily loaded mass stabilized structure floating on top of a soft soil layer is concerned, in some special cases, it is necessary to check if there is a risk of lateral sliding.

In stability calculations, a selected non-reduced design strength is used as stabilization shear strength. In evaluating of the selected design strength, the strength from laboratory tests is reduced with the correction factor q_{uf} / q_{ul}. (chapter 8.2). The binder dose to be used in stabilization is chosen such that the intended design strength can be achieved for sure. In order to determine the binder amount, a sufficient confidence coefficient is required.

When stabilizing a narrow area with a weak subsoil, where the mixing machinery advances on top of the stabilized ground, it might occur that the stability achieved is too low to proceed with work. Such problems might be faced while constructing a long and narrow road across a marshland. In order to secure sufficient stability, it is possible to install geosynthetic reinforcement (grid or woven textile) instead of a geotextile under the compaction embankment. This reinforcement can also be taken into account in the stability analysis of the final structure.

8.4 CALCULATION OF MASS STABILIZATIO SETTLEMENT

Phases of settlement:

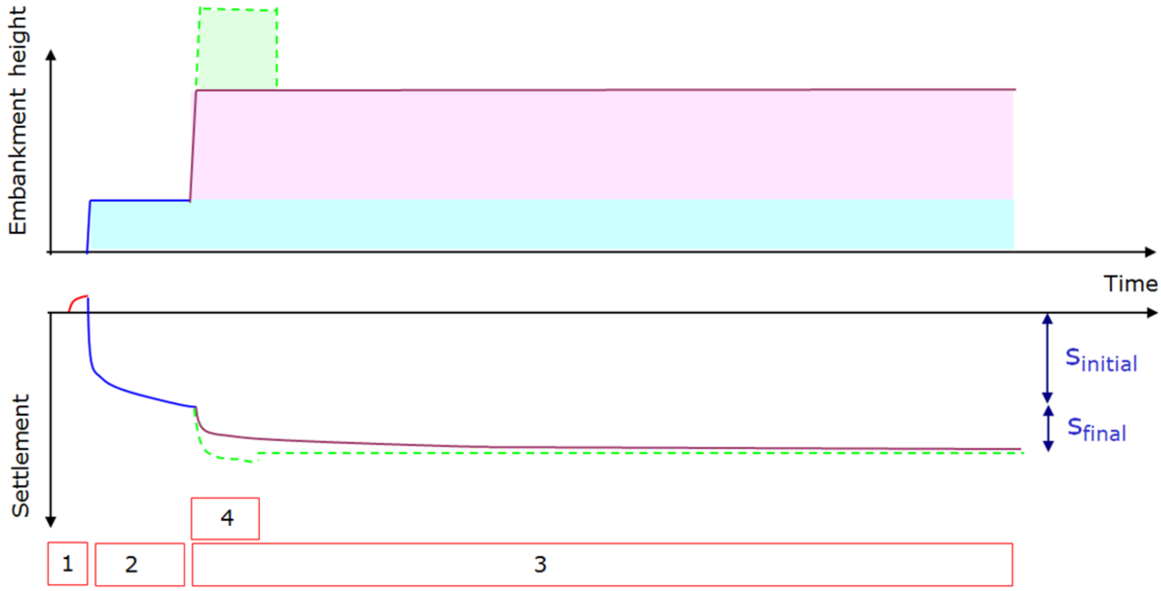
Settlements within the mass stabilized layer occur in four phases (the phases of mass stabilization settlement are presented in Figure 8.2):

1. Stabilization work: During stabilization work, dry binder is fed into the ground with compressed air. It is mixed with the soil by the hose equipped with rotating drums. During stabilization phase, this often causes some "loosening" of the stabilized soil material resulting in raising of the stabilized layer surface.

2. Compaction embankment: The biggest settlement in a mass stabilized layer occurs when initial compaction occurs under the compaction embankment. The thickness of a typical compaction embankment ranges from 0,5…1 m. The compaction embankment affects the structure during curing time.

3. Final embankment: The actual embankment is constructed on top of the compaction embankment, and, if necessary, replacing the compaction embankment material. Prior to the construction of the final embankment, it is recommended to evaluate the progress of compression of the mass stabilized layer with settlement plates.

4. Preloading embankment: If there is a need to minimize settlement during the operational period of a structure, it is recommended to pre-load the stabilized layer with final embankment load or with additional load (surcharge). If settling layers (not stabilized) remain under the mass stabilized layer and their settlement is not eliminated with pre-loading, the long-term settlement will continue. In peat stabilization, the application of pre-load is usually indispensable.



1. Stabilization work
2. Compaction embankment ≈0.5…1 m (mass stabilization hardening)
3. Final embankment
4. Preloading embankment (with or without surcharge)

Figure 8.2 Phases of settlement in mass stabilized layer and settlement time diagram. (Source: Forsman 2008).

When sulphate-bearing clay is mass stabilized, it is possible that the treated layer may expand under compaction embankment (because of the ettringite reaction). The potential expansion of the stabilized layer during curing time does not in practice cause problems in embankment structure. However, it is worth being aware of this issue if, for instance, the obtained results of the settlement calculations differ from the expected ones.

Settlement calculation:

The total settlement of the mass stabilized layer can be calculated in accordance with equation 8.1, assuming that the stabilized volume behaves as a linear elastic layer. Equation 8.1 aggregates phases 2 and 3 in Figure 8.2. (Forsman 2008)

$$S_{total} = \frac{q}{E_{50}} * h \tag{8.1}$$

S_{total} = total settlement [m]
q = stable load [kN/m^2]
E_{50} = modulus of mass stabilized soil layer [kN/m^2]
h = stabilized soil layer thickness [m]

Since the total settlement consists of settlements in various phases, this provides a ground for calculating settlement in at least two stages with equation 8.2 (phases 2 and 3 in Figure 8.2).

$$S_{total} = S_{initial} + S_{final} \tag{8.2}$$

$S_{initial}$ = settlement caused by compaction embankment [m]
S_{final} = settlement caused by final embankment [m]

By calculating separately the settlement caused by a compaction embankment, it is possible to estimate the material amount necessary for the construction of the final embankment. Additionally, the magnitude of settlement experienced in the compaction phase is needed to assess the magnitude of settlement of the final structure. In the calculation of the final settlement, the thickness of the final embankment and the stabilized layer is determined by taking into account the settlement caused by the compaction embankment.

Settlement caused by a compaction embankment is calculated in accordance with equation 8.3 (phase 2 in Figure 8.2).

$$S_{initial} = \frac{q_{compaction\ embankment}}{E_{initial}} * h \tag{8.3}$$

$S_{initial}$ = settlement caused by compaction embankment [m]
$q_{loading\ embankment}$ = compaction embankment load [kN/m^2]
$E_{initial}$ = compaction- / curing time module [kN/m^2]
h = thickness of the stabilized layer [m]

The compaction / curing time module is often approximately 0.1…0.3 MPa (100…300 kN/m^2). It can be determined by measuring the settlement occurring in a stabilization test specimen during curing time. In general, it can be expected that the level of settlement for clays and silts is ≈ 5…15 %, and for gyttja and peat it is ≈ 10…30 % of the initial thickness of the mass stabilized layer.

The settlement of the final embankment constructed on top of the mass stabilized layer after curing time is calculated in accordance with equation 8.4 (phase 3 in Figure 8.2).

$$S_{final} = \frac{q_{total}}{E_{final}} \times (h - S_{initial}) \tag{8.4}$$

S_{final} = settlement caused by the final embankment [m]
q_{total} = final embankment load (evaluated on the basis of the distance between the surface of the stabilized layer and the top of the embankment crest) [m]
E_{final} = module of the consolidated mass stabilized soil (usually about 350…450 × τ) [kN/m^2]

When compaction embankment is employed (phase 4 in Figure 8.2), it is recommended to evaluate separately the settlement caused by the impact of this structure and the settlement occurring afterwards. In settlement calculations, it also necessary to take into account the settling layers or column stabilization done below the mass stabilized stratum.

In the calculation equations presented above, the presented modules of mass stabilized layer not accurate but indicative. The modules have to be determined individually on the basis of laboratory tests' results or according to experience. The modules are not constant but they are affected by various factors, such as soil quality, binder amount and its type, load magnitude, and curing time under compaction embankment.

The time of settlement of the stabilized layer depends on many issues, for instance, on the thickness of the layer, the level of consolidation, strength development.

In case of mass stabilization, the schedule of a construction project is always to be designed individually. The indicative example presented below might be helpful in timetable planning:

- 0,5…3 months – compaction embankment (phase 2 in Figure 8.2)
- 1…3 months - final road embankment (phase 3 in Figure 8.2)
- 0…6 months - possible preloading embankment (phase 4 in Figure 8.2)
- 2…6 months – base course
- 3…9 months - surfacing

In order to update the validity of the construction project schedule and for the monitoring purposes, it is recommended to carry out settlement investigations in the stabilized layer. Settlement plates or hose settlement gauges can be used for the monitoring needs.

8.5 UNSUPPORTED TRENCH

Mass stabilization can be also applied for slope improvement in trenches. A consolidated mass stabilized layer can be utilized for making unsupported and supported trenches. Supported trenches are not addressed here and they have to be dimensioned on a case-by-case basis.

Unsupported trenches excavated in natural soil layers are commonly designed with the use of adequate empirically based tables. In case of mass stabilized soils, these tables cannot be applied automatically, that means by taking into account only the strength properties of the stabilized soil and designing the trench in the mass stabilized layer using the tables for natural soils with corresponding strength. This is because of different strength variations in natural and stabilized soils. In natural soil layers, strength variations are lower and more predictable. In case of stabilized soils, variations in strength are large and less predictable. Moreover, it is possible that in the otherwise well hardened mass stabilized layer, there are some weak zones or layers which may jeopardize the stability of the trench slope.

In dimensioning an unsupported trench in a mass stabilized layer, a potential strength variation in such a layer always needs to be taken into consideration.

Figure 8.3 illustrates the issue of strength variation in a mass stabilized layer and the potential impact of a weak zone in the case of an embankment and an unsupported trench. A limited weak zone practically does not affect the stability of an embankment in a negative way, whereas in the case of a trench it might jeopardize its slope stability. However, weak zones must be taken into account in embankment dimensioning, for example, in setting strength requirements for the mass stabilized layer based on the dimensioning strength.

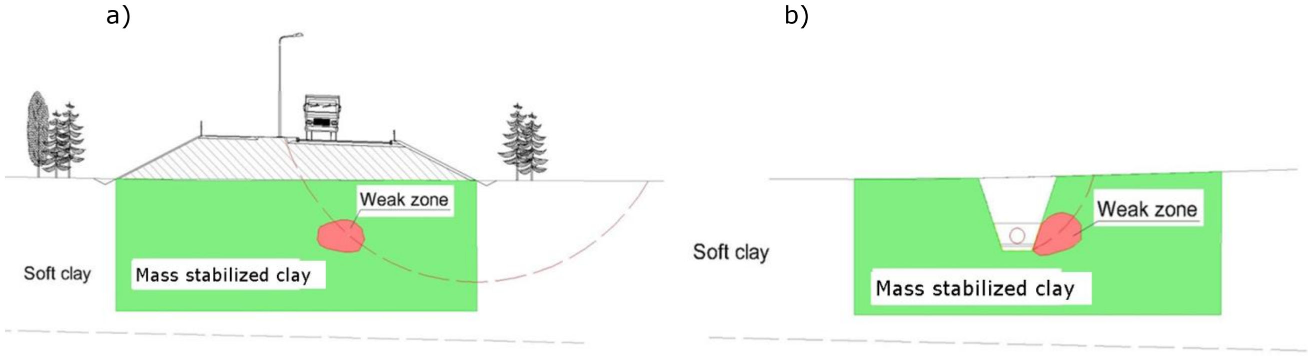


Figure 8.3. Potential weak zones in the mass stabilized layer are not relevant in an embankment with a large sliding surface a), but in unsupported trenches it might jeopardize slope stability

8.6 PROTECTION AGAINST VIBRATION

The application of mass stabilization can be useful for prevention of vibration induced by traffic and trains. For the needs of vibration prevention, mass stabilization can be employed below the surface of a road or a railroad as a subgrade improvement, or a special wall between the source of vibration and the area sensitive to vibration. Improved subgrade in a road, street or a railroad structure minimizes vibration generation, while the functioning of a vibration damping wall is based on reflecting, absorbing and attenuating the vibration wave.

Vibration damping impact of a wall structure depends on the relationship of its length, width and depth, the distance from the vibration source and the object to protected, as well as on the vibration wavelength. The wall is dimensioned in such a way that its length should be at least three times as big as the width of the area to be protected, and the depth should be of the same size as the length of the longest wave to be damped. While designing the wall location, it should be taken into account that the bigger the distance to the vibration source, the lower the vibration damping efficiency of the wall.

With respect to vibration, the most problematic areas are those which are formed of soft cohesive soils. In case of cohesive soils, such as silt, clay, peat and gyttja, the amplitude of vibration is usually the largest and so is the area of vibration influence.

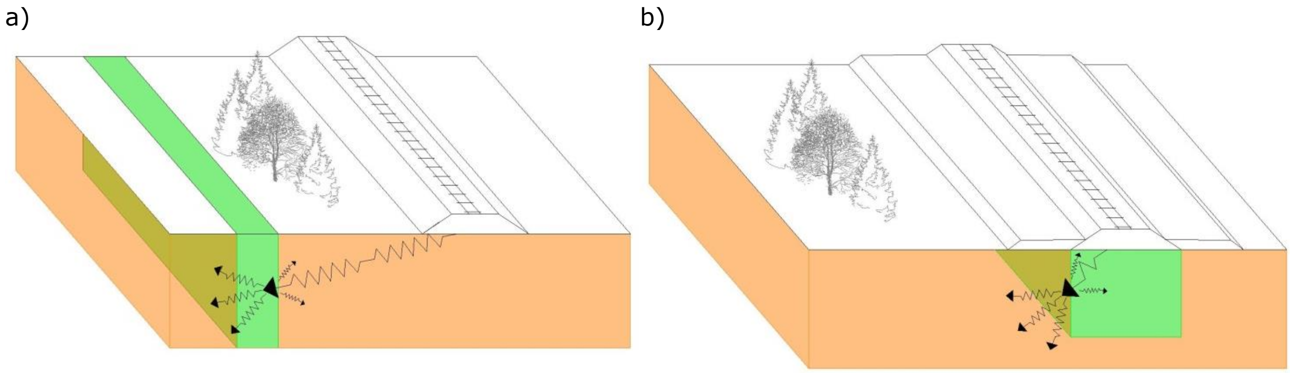


Figure 8.4. a) Mass stabilized vibration reducing wall and b) mass stabilized subgrade under a railroad or a road as a way of attenuating vibration wave

9. CONSTRUCTION

Work specifications and work execution programme

Stabilization design includes construction work instructions, rules and quality control measures. Design consists of work specification, quality control plan and design drawings. The document is commonly elaborated by a developer's design engineer.

The contractor creates a work execution plan which shows the location of the areas to be mass stabilized, and the location of grids and their numbers. The total area is divided into sub-areas (stabilization grid, stabilization block). For the constructor, one block functions as a basic unit of stabilization into which a certain amount of binder is fed. The size of the stabilization block is commonly about 5 × 5 m^2.

Stabilization work can be roughly divided into the following stages:

- Site preparation: step I:
    - removal of topsoil, identification and marking the location of pipelines, cables, culverts and other structures on the ground
- Site preparation: step II
    - arranging for access to the site and connection with existing roads for lorries and equipment, fixing position of the site office and refuelling points and their construction
- Measurements in the site, setting out the corners of the stabilization area and the stabilization grid, ground levelling
- Construction of potential working platform
- Mass stabilization work (=mixing binders with aggregate)
- Construction of compaction embankment
- Quality control

Preparatory works

Preparatory works in the stabilization site include harrowing and removal of trees, shrubs, stumps and roots, as well as all other materials and structures (e.g., culverts) that would hamper the stabilization process. Moreover, fillings that would hinder stabilization are to be removed prior to the start of work from the area of concern.

For the purpose of the stabilization works, the exact location of pipelines, cables and other structures of this type needs to be known. Necessary traffic and transportation arrangements have to be sorted out well in time. It is also necessary to reserve a suitable place for the storage of binders.

Stabilization work

The location of the stabilization grid is set out before the launch of stabilization. Measurements can be carried out with the help of a stabilization machine equipped with a GPS unit or performed manually (using a tacheometer, GPS device). Prior to the start of the actual stabilization work, trial stabilization may be executed. It allows to test whether the designed strength can be achieved with the planned amount of binder. Generally, the actual stabilization follows immediately the trial phase.

In stabilization work, it is important to feed the binder into the aggregate in a uniform and homogenous way. The allowed tolerance is usually within the range of ± 0.25 m (x,y,z).

Since every stabilization project is unique, stabilization work always needs to be designed on a case-by-case basis. In some events, there is a need to drain the mass stabilized area by pumping or by constructing ditches. Water flowing away from the mass stabilized area needs to be monitored visually or, if necessary, by sampling, in order to ensure that no harmful substances are released to the environment. In some cases, it is also possible to construct a settling basin to collect and then to remove water from the area. In other cases, it may be required that water is added to the stabilized mass in order to ensure a successful stabilization process allowing to reach a target strength. Water addition is applied to such soils as, for instance, dry silts.

Providing both mass and column stabilization methods are employed in the target site, it is necessary to schedule the project such that column stabilization is easily implemented in the mass stabilized soil volume. Column stabilization can be carried out through the mass stabilized layer. This requires paying a special attention to the development of mass stabilization strength. Generally, column stabilization can be executed almost immediately after the completion of mass stabilization. In most cases, clay layer placed under peat stratum is column stabilized first and this requires a special working platform.

<u>Binder feeding and compaction embankment construction</u>

The precondition for successful implementation of mass stabilization is uniform mixing of binder with the soil mass. It needs to be taken into account that different soil layers set different requirements for binder feeding and mixing.

When stabilization block is used as the basic unit, the amount of binder to be fed is calculated for each block separately. Generally, the amount of binder fed must not deviate from the designed value more than 5%. If necessary, samples can be collected and binder amount can be checked with content measurement tests. Binder should be fed to the planned depth which is marked on the design drawings. Binder mixing efficiency surveillance is part of the overall quality control. The efficiency of mixing work can be also monitored with various 3D-system units if the stabilization machinery is equipped with such.

A report of stabilization work progress for each block is compiled and it includes the following information:

- Identification number and location of the stabilization area
- Identification number and location of the stabilization block
- Coordinates of the stabilization block (x,y,z)
- Stabilization block area; bottom and top surface level; depth of the stabilization block
- Amount of binder fed (kg/soil-m^3)
- Binder quality (e.g. cement type used)
- Amount and quality of binder-consignment
- Potential problems with binder feeding and other observations
- Date of stabilization work implementation
- Weather conditions during stabilization work

Also, stabilization work execution maps are printed for the needs of reporting (including ACAD versions).

During the binder feeding and mixing stage, the stabilized soil layer becomes loosened. A preloading/ compaction embankment is used on the mass stabilized area to ensure consolidation of the stabilized layer. This also allows for a faster start of reactions in cement and the removal of surplus water from the mass stabilized structure. The thickness of the embankment is usually 0,5…1,0 and strainer cloth is placed on its top.

It is particularly important to construct a compaction embankment during the same working shift in stabilization of peat. It can function as the lowest component of the structure or the embankment fill, in which case the choice of a suitable material depends on the type of structures to be constructed afterwards. If the compaction embankment is to be removed before the continuation of construction works, the material it is made of needs to be considered on a case-by-case basis bearing in mind the possibilities for its future reuse.

Issues to be taken into account during strengthening time

Heavy equipment movements in the stabilized area immediately after stabilization should be avoided. Embankments can be constructed to the full height only when the planned strength is achieved. Excavation works are also not allowed to be carried out in the stabilized area and its immediate vicinity before the strength has become adequate. During curing time, quality control drillings are done and if necessary, they provide also stabilized material samples for laboratory tests.

Issues to be taken into account during mass stabilization implementation

Stones, tree trunks, stumps and other obstructions in the ground belong to the factors slowing the process of stabilization and they can be harrowed from the area to be stabilized before the start of the actual stabilization work.

If the soil to be stabilized consists of very hard clay, premixing or, the so called, pre-homogenization may offer a reasonable solution. If necessary, water or other components are added to very inhomogeneous masses. In general, it is possible to mix the treated layer with various subcomponents such as binders or additional aggregate materials, e.g., sand. Prior to the actual stabilization, these components are spread on the surface of the soil mass to be stabilized as a separate layer or if necessary, they are premixed with excavator.

The above-mentioned methods improve the final result of mass stabilization but they decrease stabilization work efficiency. In some cases, particularly in the context of peat stabilization, the result of stabilization can be improved by extending the scope of stabilization to a layer that is below the soft, wet and poorly consolidating stratum. With the movements of the mixing head, aggregate which better fit for stabilization is lifted upwards to the aggregate layer which is challenging for stabilization. In this way, the quality of treated aggregate is improved with a positive overall impact on the final result of the stabilization process. It is also possible to spread surplus clay on the surface of a peat layer already prepared for stabilization and mix them in order to increase the content of mineral matter.

After completion of mixing works, strainer cloth is spread on top of the stabilized layer and, depending on the situation, a 0.5 ... 1 meter thick loading embankment is constructed. It functions as a working platform for the stabilization equipment to proceed with mixing process. Vertical load exerted on the stabilized mass has a compressing effect on it and due to this, an overall positive impact on the strengthening process.

During stabilization work, the following aspects concerning the equipment and the construction site should be taken into consideration:

- weather conditions/ temperature
- space available for the equipment
- variations in the site ground conditions
- transportation of binder to the site and on the spot; binder storage
- initial strengthening of the stabilized layer and its effect on work progress

Stabilization can be carried out in winter conditions but very severe frost slows down the process. In Finland, mass stabilization was done in temperatures as low as -30 °C. If the ground is frozen, it might be necessary to use a drop-hammer to enable excavation works. This will, however, reduce work efficiency.

Air temperature can affect strengthening process occurring in the stabilized structure. For example, gypsum, slag, fly ash and lime belong to slow binders with curing reactions persisting for a long time after mixing. On the contrary, cement is a hydraulic binder that hardens faster. In mass stabilization, it is common to apply mixtures of cement and lime, as well as other type of binder combinations.

To ensure smooth operations in the site, it is necessary to arrange sufficient space for car and machinery parking, lorry manoeuvring, binder feeding units, various storage needs and if necessary, silos. Binder refill base occupies most space and it needs to be placed on a load-bearing platform. The required space is about $10 \times 20\ m^2$.

The properties of subsoil in a single site can vary considerably. Areas with very soft subsoil may hamper operating and moving the machinery. To avoid this problem, it is necessary to use a wooden or steel grate, timbering, pontoons or other temporary working platforms.

In some cases, binder amount is increased in the initial stage of work in order to allow for earlier and safer movement of machinery on the stabilized area. With the use of fast curing binders, it also possible to enable fast progress of work.

The pressure feeder feeds dry binder from the container through the hose. Pressure feeders are refilled with binder that has been transported to the site and stored in the refill base containers. Binder availability must always be ensured. Binder supply wise, technical aspects need to be considered together with economic and logistic issues. Binder storing in the site requires special preparations. Binder agents need to be dry and powder-like when they are applied with the use of pressure feeder. Most commonly, binder is transported with tanker lorries. For the needs of a small construction site's logistics, it is possible to transport binder in bulk bags. The appropriate techniques of binder delivery and storage include:

- transport with tanker lorries
- transport in bulk bags
- storage in a shed
- storage in a silo

Binder is weighted by its supplier and this information is passed to the constructor. The pressure feeder is equipped with a scale which allows for measuring binder amount fed to a stabilization block. The accurate scales allow for monitoring and controlling binder consumption.

The order of main stages of mass stabilization project:

1. Topsoil removal
2. Removal of all objects that disturb stabilization works and filling of ditches and hollows
3. Marking of stabilization area and block
4. Ground level measurements
5. Stabilization work
6. Loading embankment/ working platform
7. Quality control of the stabilized layer
8. Quality control and follow-up of the stabilized area

10. QUALITY ASSURANCE

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 individual components of a constructed structure are compared to the requirements set by the design. Also, the compliance of the overall structure with the design is investigated. Quality control checks concerning the final structure are carried out both by the independent and the field quality inspectors. The constructor bears responsibility for quality control and management of stabilization work.

Quality assurance activities start simultaneously with the launch of stabilization works. The measurements of quality assurance vary depending on the site. A log sheet is maintained during stabilization project (see chapter 9).

The routine quality control tests recommended are presented below. The list of necessary tests and methods to be used is determined case-by-case.

Field investigations:

The quality control tests carried out in the field include soundings, test pits, settlement plates and, if necessary, sampling. The complete list is outlined in the work specifications. The most common methods of sounding include column and vane penetrometer tests. The tests are carried out, at a minimum, as many times as outlined in the work specifications. Depending on the target, they are usually conducted 7…90 days after stabilization. Tests carried out after 7…14 days are only tentative, whereas test carried out between days 28-90 give some approximate information on the final result quality. Depending on binder type, the final strength can be achieved only after longer period of time. Therefore if needed, part of the quality control soundings can be conducted in 6…12 months after the completion of stabilization work.

Should quality control soundings show that the strength requirements are not complied with, test are often repeated after some time. The longer period of curing time allows the slowly reacting binders to achieve the required strength, thus eliminating the need of corrective measures and additional investigations. In case the target strength is not achieved with longer curing time and/or there is a need to identify the reason for this situation, additional tests are carried out including the investigation of binder amount and distribution, the adequacy of mixing and binder composition. Moreover, the impact of the lower achieved strength on the final structure and the stability of trenches and excavations is investigated with geotechnical calculations.

Sounding methods:

The most common methods of quality control soundings include column penetrometer and vane penetrometer for columns. The aim of the column penetrometer tests is to measure indirectly the shear strength of mass stabilization. The test results obtained with vane penetrometer are used for calibrating column penetrometer bearing ratio. Column penetrometer and vane penetrometer tests are made using a ground investigation rig (Figure 10.1). Both methods are presented in a more detailed manner below.

Also the CPTU test method is employed for the needs of quality control investigations. Its application depends on the type of soil to be tested and the desired strength.

Since the cross-sectional area of a typical cone tip is small, the results of one test are not representative enough. Thus, it is advisable to conduct more CPTU tests in comparison to, e.g., column penetrometer tests, and not to replace column and vane penetrometer tests with this method only.

Soundings are conducted on uncovered surface of the mass stabilized layer. Since strainer/reinforcement cloth may be on the way of the sounding rod and stick to it, this can be avoided by cutting a whole in the cloth.

Figure 10.1 Ground investigation rig (photo: Fredrik Winqvist).

Column penetrometer for deep stabilized soil

In this method, a mechanical penetrometer equipped with two (or three) vanes is pressed down (without rotation), and the compressive strength employed is measured at the upper end of the penetrometer rod. The cross-sectional area of the penetrometer is A = 100 cm^2 and the diameter D = 375 mm (other dimensions are also used). The device was originally developed in Sweden at the start of the 1980's for stabilized columns and a slightly adapted version was used in Finland from 1981. The aim was to shape the penetrometer head so that the sleeve friction would be as little as possible and that the penetrating resistance would be mainly formed outside the centre part of the column.

Because the cross-sectional area of the column penetrometer is ten times as large as that of a normal CPT cone, its application area (due to its capacity) is in stabilized soil which shear strength S_u < 200 kPa. Because the penetrometer is durable, the dynamic penetration method has been experimented with in the harder columns, although the interpretation of results has then proved more difficult. As the dimensioning value used in engineering is either uniaxial compressive strength or shear strength, the measured penetration resistance is converted into shear strength by dividing it by the factor N_c = 10 (in Sweden) or N_c = 10…15 (in Finland). In Finland the shear strength values measured by the vane penetrometer are used in defining the N_c-factor.

Vane penetrometer for deep stabilized soil

This method has been used in Finland since the beginning of the 1980's. The device is best suited for the examination of stabilized soil which shear strength S_u < 200 kPa. Because the core of soft lime-columns was softer than the sides, the vane penetrometer has been designed with as large a diameter as possible (D = 130/160 mm, H = 0,5 × D). The sleeve friction caused by the rods in the available models is eliminated by an angular motion switch above the vanes.

Depending on the length of the columns or depth of mass stabilized soil and the desired measurement density, vane penetrometer test is carried out at intervals of 0.5 or 1.0 meter. It is customary for vane penetrometer tests to be conducted much less frequently than normal penetrometer tests. The vane penetrometer tests are used in particular as an aid in interpreting the results of conventional penetrometer tests.

Vane penetrometer for columns　　Column penetrometer　　Vane and column penetrometer

Figure 10.2 Vane penetrometer and column penetrometer for column and mass stabilized soil.

a)　　b)

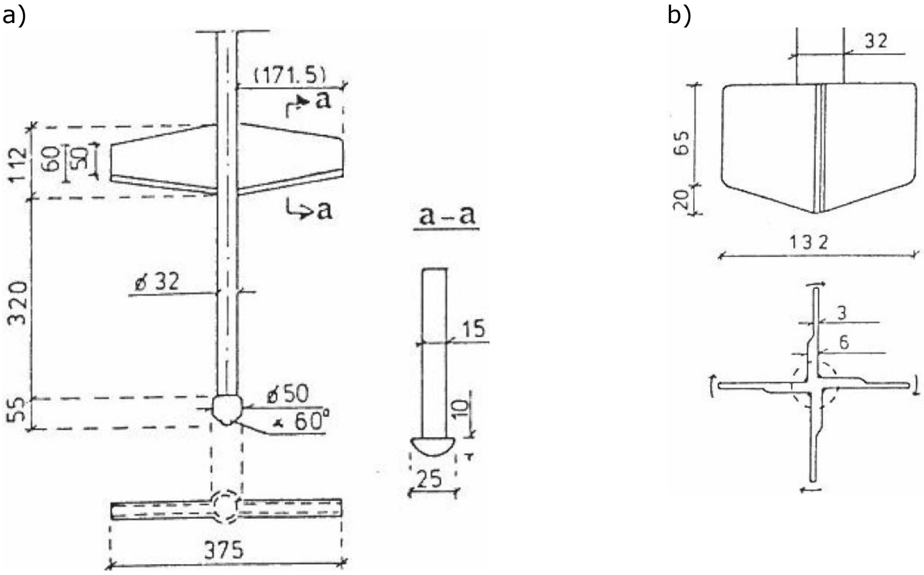


Figure 10.3 Dimension of a cone and rod in a) column penetrometer b) vane penetrometer (STO 1991)

<u>Sampling and other field investigation methods:</u>

One of the challenges of sampling in mass stabilization investigations deals with the fact that the possibility to collect an undisturbed sample varies to a large extent. If continuous sampling is conducted in the stabilized layer, penetrometer tests can be employed for evaluating strength (variations of strength) and Niton tests for the determination of variations in binder amount. Moreover, it is always worth taking pictures of samples and doing visual evaluation of their homogeneity and its variations. It is recommended to perform triaxial compression tests, as in the case of even slightly disturbed or fractured samples, the strength values obtained with unconfined compression test are too low.

Test pits allow for visual evaluation and documenting the quality and homogeneity of mass stabilized soil. Also samples can be collected in test pits in order to determine pH and water content of the stabilized mass. In addition, test pits enable collecting samples for determination of strength and conducting penetrometer, miniature vane shear, and/or Niton tests.

Settlement plates are employed to measure the settlement of stabilized mass. Settlement plates allow also for some rough estimations of lateral displacements but the measurement accuracy is only indicative.

Niton-analyzer (Figure 10.4) enables to analyze the homogeneity of stabilized soil in the field. It provides a possibility to assess the amount of binder by measuring calcium content in the stabilized mass and by comparing the obtained results with the "calibrated results" prepared for the aggregate and binding agent. Niton-analyzer in based on the x-ray fluorescence spectroscopy method. It determines the chemistry of a sample by measuring the spectrum of the characteristic x-ray emitted by the different elements in the sample when it is illuminated by x-rays. These x-rays are emitted either from a miniaturized x-ray tube, or from a small, sealed capsule of radioactive material.

Figure 10.4. Niton-analyzer.

Figure 10.5 Various penetrometers

With the help of a penetrometer (Figure 10.5), it is possible to make some observations of approximate strength of the soil material. The test method consists of pushing an instrumented cone, with the tip facing down, into the ground at a controlled rate. It forces failure of the soil ahead the tip and the resistance is measured in order to determine the material strength.

The miniature vane shear test (Figure 10.5) is a field investigation method to determine the strength level in not stabilized and stabilized soil masses. The test starts by pushing the vane and the rod vertically into the soft soil. The vane is then rotated at a slow rate of 6° to 12° per minute until a maximum torque is reached and the shear strength value is visible on the scale mounted on the handle.

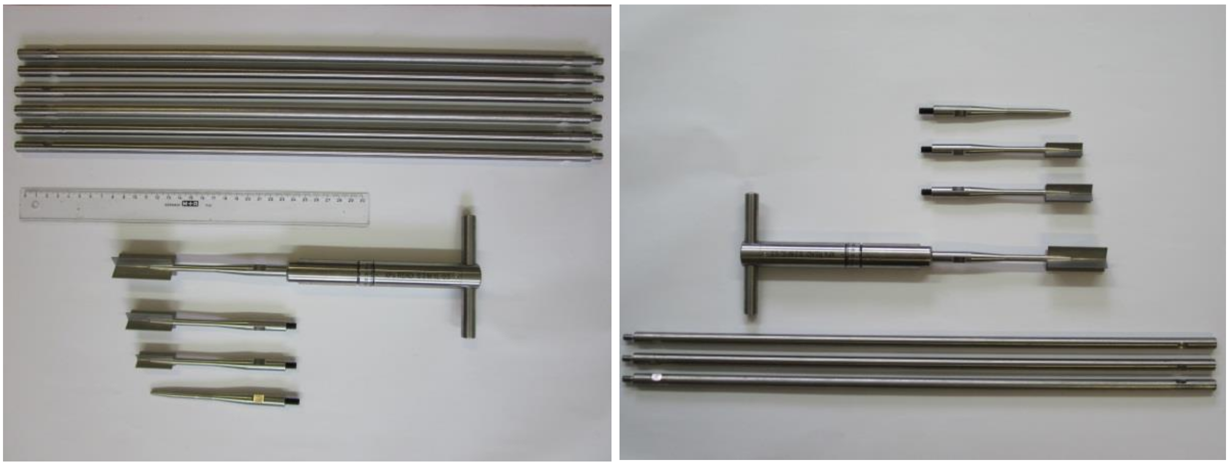


Figure 10.5. Miniature vane penetrometer

<u>Quality control laboratory investigations</u>

The quality control investigations carried out in the laboratory include compression strength tests, determination of the level of homogenization with the analysis of binder amount, determination of water content, pH tests, and for contaminated soils, also leaching tests.

Material strength is measured with compression strength tests. Base on the test results, it is possible to evaluate how strength has developed in the stabilized mass. For the needs of quality control, laboratory tests are commonly performed on samples collected in the field, i.e. made of the material originating from the stabilized structure. It is also possible to make samples from the material collected just after mixing. In this case, the collected material is packed into test cylinders and cured in the conditions complying to the site conditions. After curing time, a cylindrically shaped test piece is loaded with a constant speed until it breaks. The loading rate is usually 1 mm/min.

In determining water content, the sample water content is measured in relation to the amount of dry matter.

The pH is measured in the soil aggregate before stabilization and in the stabilized mass. Depending on the target, pH tests can be made for samples originating from various depths. The result is evaluated on the basis of changes in pH caused by the addition of binder.

Binder amount determination allows to check the actual amount of binder in the stabilized soil.

If necessary, leaching tests are conducted for mass stabilized contaminated soil material. The tests demonstrate what harmful substances leach from the soil. The duration of leaching tests including reporting is about 3 months.

Quality assurance

- Intrinsic part of stabilization work
- Field investigations:
    - soundings, test pits, settlement plates, sampling
- Laboratory tests:
    - stabilization tests, homogeneity evaluation, water content, pH, binder determination, leaching tests (contaminated soils)

BIBLIOGRAPHY

Deep Soil Mixing Ltd. UK, brochure Poole Quay Extension – RNLI, 2 s.

EuroSoilStab. 2002. Design Guide Soft Soil Stabilization,

EN 14679. 2005. and AC. 2006. Execution of special geotechnical works. Deep mixing and its corrigendum

Forsman, J. 2008. Stabilisation project - step by step, designing. International Mass Stabilisation Conference 2008 8.-10.10.2008, Lahti, Finland

Forsman, J. 2008. Kotolahden ratapiha, Kotka, rakennussuunnitelma.

Halkola, H. 1999. Keynote lecture: Quality control for dry mix methods. Stockholm 1999. Proceedings of the International Conference on Dry Mix Methods for Deep Soil Stabilization, 13-15 October 1999, Ed. by: Bredenberg, H., Holm, G., Broms, B. Brookfield, Rotterdam, 1999.

Hautalahti, P., Halkola, H & Puumalainen, N., 2007. Kivikon teollisuusalueen stabiloinnin koerakentaminen. Geoteknisen osaston julkaisu 92/2007. 105 s.

Heikkilä, J. 2006. Massastabilointi stabiliteetin parantamisessa Tampere – Seinäjoki radalla. SGY, Syvä- ja massastabilointipäivä. 24.8.2006, Otaniemi.

Kiviniemi, O. et. al. 2012. Tuhkarakentamisen käsikirja. Energiatuotannon tuhka väylä-, kenttä- ja maarakenteissa. 13.1.2012. 65 s + liitteet.

Koivisto, K., Forsman J. & Leppänen, M. 2004. Column and Mass Stabilisation of the Yards of IKEA in Vantaa, Finland. NGM 2004, Ystad, Sweden, 19.-21.5.2004.

Liikennevirasto 2010. Syvästabiloinnin suunnittelu. Tien pohjarakenteiden suunnitteluohjeet. 11/ 2010 Liikenneviraston ohjeita. 56 s. + liitteet

Lindroos, N. et al. 2012. Stabilisation as an alternative for mass exchange for clays with high sulphide content. WASCON 2012 Conference proceedings.

Nauska, J. & Havukainen, J. 1998. Esirakentaminen 1998. Geoteknisen osaston tiedote 77/1998. 105 s.

Syvästabilointiohje STO-91. 1992. Rakennusaineteollisuusyhdistys ry ja Rakennustieto Oy. Helsinki. 52 s.

Tikkanen, V. 2006 Massastabiloinnin yleisiä hyödyntämismahdollisuuksia. SGY, Syvä- ja massastabilointipäivä. 24.8.2006, Otaniemi.

Photos:

ALLU Valencian satama, Espanja

Aspholm, Jonas 2011 Mustasaari

Havukainen, Jorma 2004 Vuosaaren satama, Helsinki

Leppänen, Mikko 1995, 1996 Råneå ja Skyttorp, Ruotsi

Nuotio, Aino-Kaisa 2013 ja 2014, Ida Aalbergin puisto, Helsinki

Winqvist Fredrik, Arabianranta, Helsinki