ANNEX 13

LIFE09 ENV/FI/575

International guidelines on the methods of converting surplus soft soils into useful earth construction materials and on how to use them in the construction of different applications

ABSOILS - Sustainable methods and processes to convert abandoned low-quality soils into construction materials

With the contribution of the LIFE financial instrument of the European Union

LIFE+2009 DEMONSTRATION PROJECT


LIFE09 ENV/FI/000575
Cofinanced by EU LIFE+ Environmental Policy & Governance programme
EU:n LIFE+ -ympäristö- ja hallinto- ohjelman osarahoittama hanke
ABSOILS:
Sustainable Methods and Processes to Convert Abandoned Low-Quality Soils into Construction Materials

Table of Contents

INTRODUCTION

Construction activities are among the biggest waste producers in Europe. Waste rock, redundant soil are and sediments the second largest waste stream in Finland. Finland shows also a very high percentage of average annual use of material - 35 tonnes per person - whereas the average in Europe is 16 tonnes per person. Finland is constantly undergoing a process of infrastructure development. The development of industrial activities frequently results in a demand for a new land in the vicinity of the main operation. In many cases, there is a shortage of land that is characterised by good geo-technical features or there is a need to rehabilitate or clean-up the contaminated land. In such cases, the most common solution is mass exchange including the transportation and landfilling of the poor quality soils and the quarrying and transportation of virgin materials. Quarrying also leads to deforestation, loss of landscape value, surface and ground water pollution.

Some of the left-over materials like stone materials can easily be reused in the on-going and future construction works especially, e.g. in noise barriers and fillings for landscaping, but there are other materials (spoils) like muddy clay, silt, humus and peat, fine sand and moraine which are challenging for reuse. Unfortunately, landfilling is a common practice as soft soils are generally considered unsuitable construction material. This exerts considerable negative impact on environment due to associated transportation and the need to increase landfill capacity. In many cases – especially in the vicinity of cities – surplus soils landfill capacity is exhausted and soil masses need to be transported for considerably long distances to available reception places. In general, landfilling of soft soils brings about the necessity of importing non-renewable virgin materials (e.g. natural gravel or crushed rock) as replacement. This requires quarrying and transportation with all the associated negative environmental impacts such as landscape deterioration, deforestation, ground water pollution and greenhouse gas emissions.

At the same time, various industrial activities generate versatile waste streams which in most cases are still deposited in landfills. From the economic and environmental point of view, this is constitutes a considerable loss with serious negative impacts on the state of the environment and the competitiveness of the EU. With the application of suitable methods waste generated by the industry can be transferred into valuable materials which allows for the treatment of poor quality soils and sediments.

With the use of a proper ground improvement method, various soft soils such as clay, gyttja and peat can be converted into useful construction material. The method presented in this handbook is mass stabilization. The intent of mass stabilization 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 guidelines use the knowledge and experience gained in the framework of the ABSOILS project carried out in 2010-2015. The Absoils project came as a response to the problem of surplus, excavated soft soils resulting from infrastructure development.

The aim of the Absoils project has been to demonstrate the practical implementation of four challenging types of civil-engineering applications including flood barriers, noise barriers, supporting banks and landscape construction.

During the project duration, it has turned out that it is not always possible to draw a clear border among the types of the applications. Most of the pilot applications have combined some of the features of the applications described above.

1. MASS STABILIZATION METHOD

The general principle of the mass stabilization method is presented in Figure 1.1. 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.

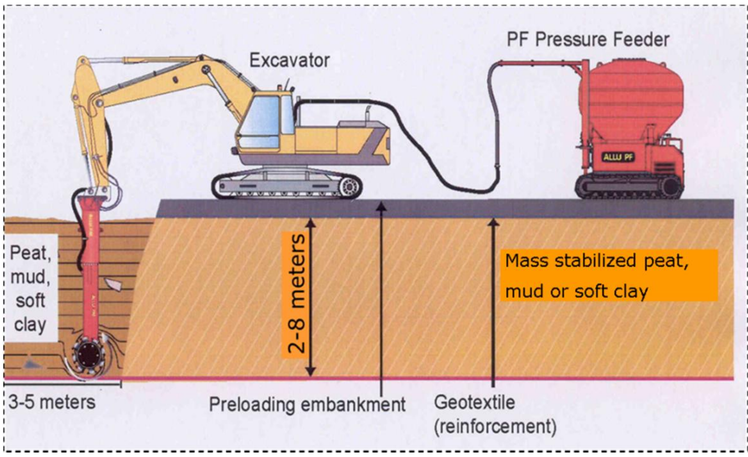


Figure 1.1 Principle of the mass stabilization method and equipment

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.

Figure 1.2 – 1.3 Mass stabilization process at the Absoils pilot site: Jätkäsaari, Helsinki

2. 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 (Figures 2.1-2.2). 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 (Figures 2.3–2.4). Dry binder is transported into the mixing unit from the motorized pressure feeder using compressed air (Figure 2.1-2.2). 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.

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 2.1 – 2.2 Mass stabilization basic equipment with the mixing unit attached to the excavator and connected to the pressure feeder.

Figure 2.3 – 2.4 Mixing drum of the mixing unit used in mass stabilization

3. BENEFITS OF MASS STABILIZATION AS COMPARED TO SOME OTHER FOUNDATION ENGINEERING METHODS

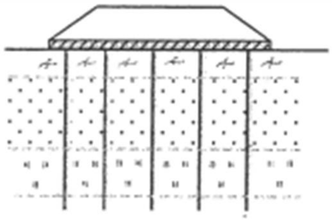
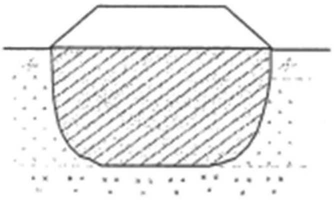
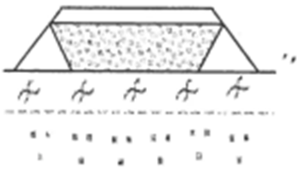
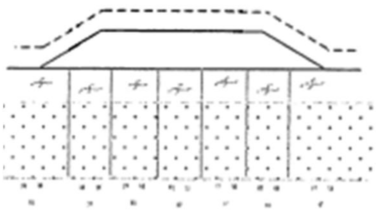
The application of mass stabilization for the treatment of excavated soft or contaminated soils confers significant benefits:

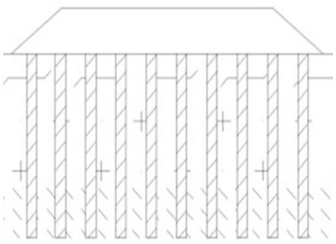
- Low quality masses can be processed with mass stabilization allowing for their utilization, thus minimizing the need for natural aggregates
- Mass stabilization eliminates the need to transport and landfill low quality soil masses
- Mass stabilization of contaminated soils leads to transformation of 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 3.1. 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.

4. 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.

4.1. Mass stabilization influence on soil properties

Influence on soil index properties

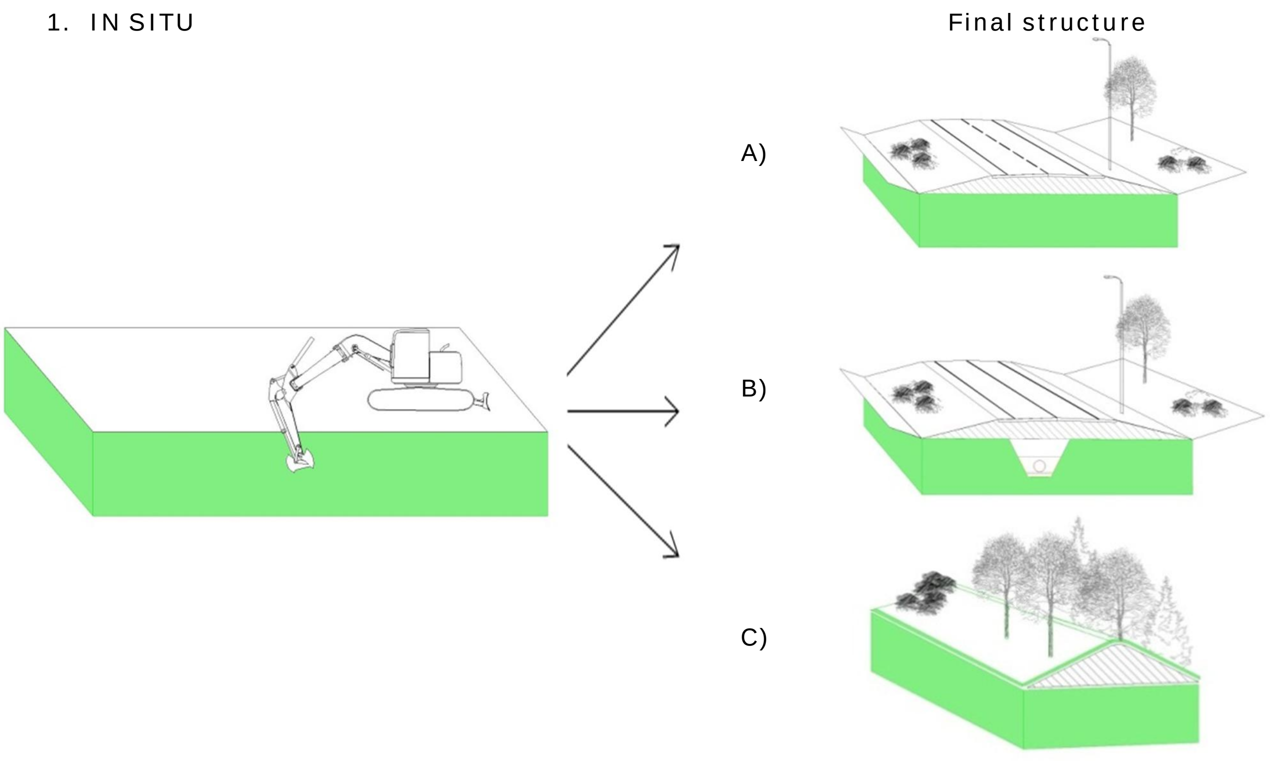
Mass stabilization significantly alters the geotechnical characteristics of soil. The result of the mass stabilization process and its rate of change are influenced by various factors, such as the type of soil, the type and quantity binder used, curing time, temperature and compaction load. Mass stabilization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

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



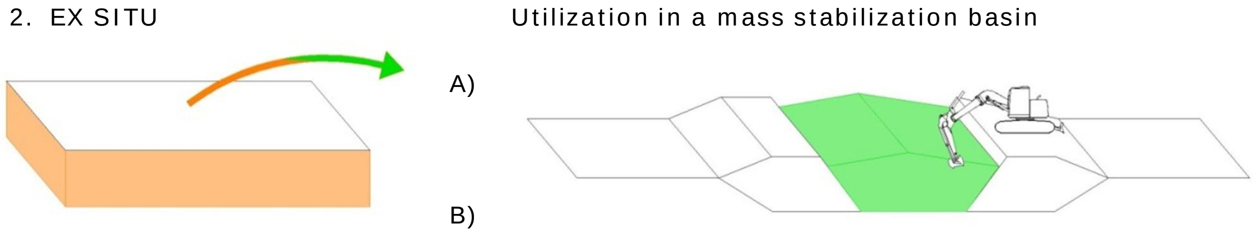
A) Subgrade improvement of a road embankment with mass stabilization

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

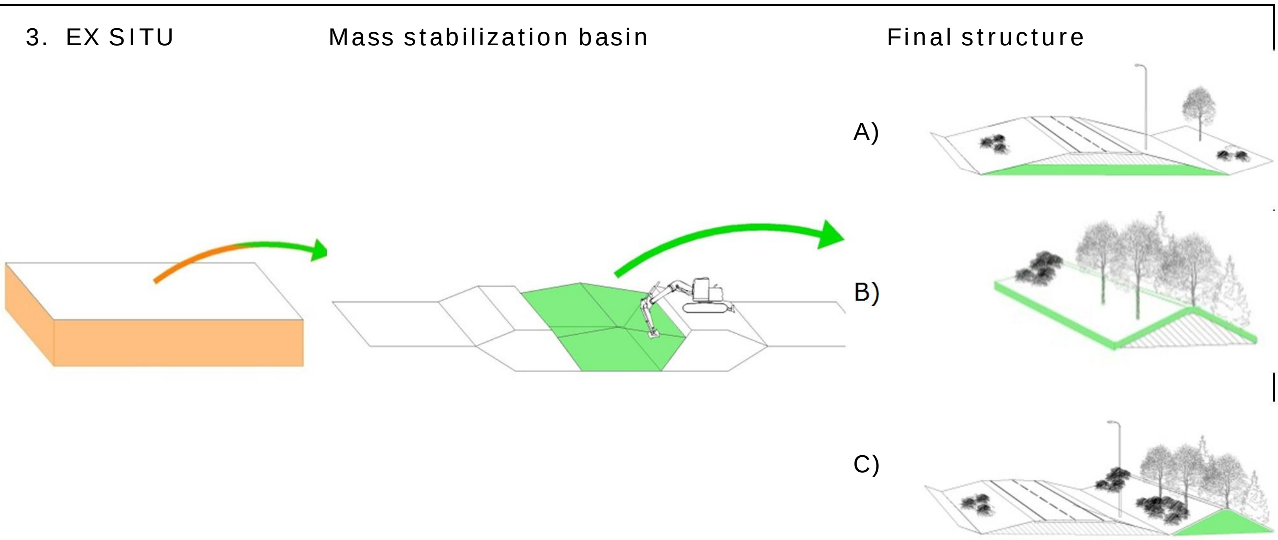
Figure 4.2 In situ mass stabilization at the Arcada2 pilot site (2011).



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 4.3 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 4.4 Ex situ stabilization: material mass stabilized in a basin is utilized elsewhere.

Figure 4.5 Mass stabilization basins of the Jätkäsaari I pilot (2011)

5. APPLICATIONS OF STABILIZED SOILS

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

The examples of the applications presented below are based on the experience gained in the framework of the ABSOILS project.

5.1. 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 5.1. If necessary, mass stabilization can also be applied to strengthen the subgrade of a wetland.

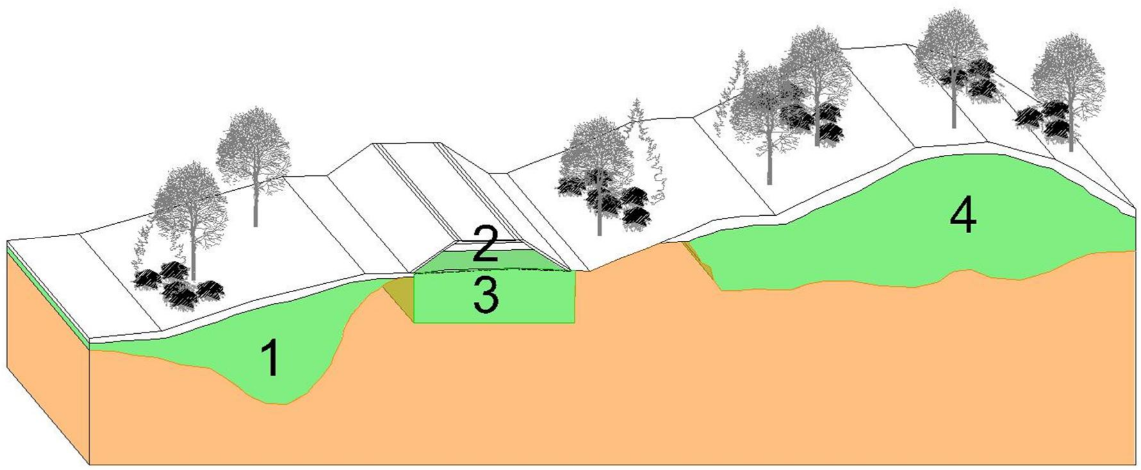


Figure 5.1 Filling carried out with the use of stabilized poor quality, surplus soil in green areas development projects and landscaping: 1) landscaping filling, 2) filling of a path embankment, 3) landscape hillocks and 4) subgrade improvement of a path

a) b)

c)

Figure 5.2 Ida Aalberg park in Helsinki: a and b) utilization of the stabilized masses from Jätkäsaari II pilot in landscaping, c) ready park

5.2. Noise barriers

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.

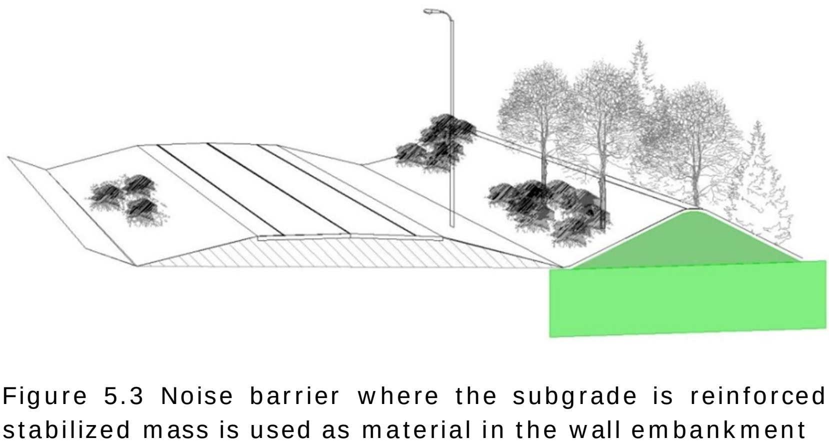


Figure 5.3 Noise barrier where the subgrade is reinforced with mass stabilization and the stabilized mass is used as material in the wall embankment

Figure 5.4 Test noise barrier constructed with mass stabilized sediments– Jätkäsaari III pilot site (2015)

The most important technical properties of mass stabilized sediment are the workability, shear strength, stiffness and the settlement properties. In case where the stabilized sediment is used as a landscaping filling, or in gentle sloped hills in parks, the demands for the material are low. When the stabilized sediment is utilized in angularly shaped deep sloped noise or flood barriers, the demands are higher.

5.3. Flood protection applications

Flood protection is defined as the design and construction of permanent structures that eliminate or lower the risk of flood damages. In 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 embankment.

Stabilized soft clays can also be used for raising the level of a construction to prevent flooding. In the Dog Park in Espoo – the pilot application carried out in the framework of the Absoils project - raising of the ground level was carried out with surplus soft soils (transported from an adjacent construction site) which were stabilised together with the upper part of the original soil (soft clay with a low load bearing capacity). The target is to reduce the occurrence of flooding to less than once in 20 years.

a) 

b) 

Figure 5.5 a) Mass stabilization work carried out in winter conditions in the Perkka Dog Park in Espoo b) Dog Park under construction

5.4. Light weight structure

Stabilized clay can be utilized as a light weight structure replacing blasted rock embankment placed on top of a clay layer.

Such structure was tested in the framework of the Absoils project, in Arcada II site, in Helsinki. The structure was designed to replace an old embankment floating over a soft clay layer. The area had low stability and load bearing capacity. The site was originally filled from the sea with blasted rock in 1960's. The original aim was to replace the existing clay with blasted rock to create a foundation for a new highway. However, because of the deep clay layer and difficult circumstances the mass exchange failed leaving the blasted rock to float on top of the clay layer.

In the Arcada II, the aim of the project was to improve the area for construction use by removing contaminated soils, lightening the blast rock embankment, installing steel-pipe piles for a pile beam and plate structure to stop the lateral expansion caused by the old embankment. In this case the Absoils project, the focus was on the construction of a stabilised “light weight” structure with surplus soft clays brought to the Arcada II site form adjacent sites which could not utilise those clays.

“Light weight” material means in this case that the stabilised clay was actually lighter than the existing blasted rock material, which was replaced ($\gamma'_{clay} \approx 5$ kN/m^3 and $\gamma'_{blasted\ rock} \approx 10\text{-}13$ kN/m^3 under water level). That is why the stabilised clay was called “light weight” material, although it did not fill the criteria set for the light weight material in standard SFS-EN 13055-2.

Figure 5.6 Mass stabilization in progress

Figure 5.7 Piling works in progress

Figure 5.8 Removal of original filling

Figure 5.9 Stabilization basin – stabilized clay in front, clay waiting for stabilization at the back

5.5. Landfill bottom, cover and other barrier structures

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.

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.

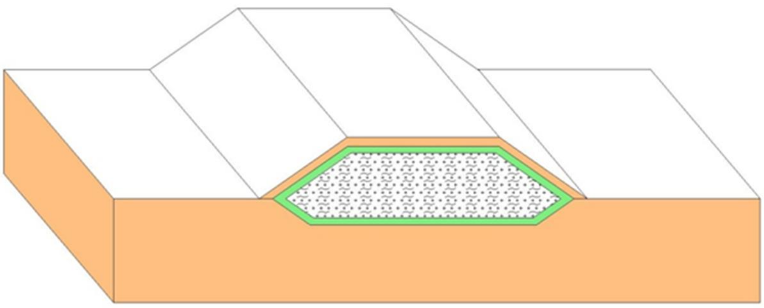


Figure 5.10 Landfill bottom, cover and other barrier structures

6. MASS STABILIZATION IN PRE-CONSTRUCTION PROJECTS

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.

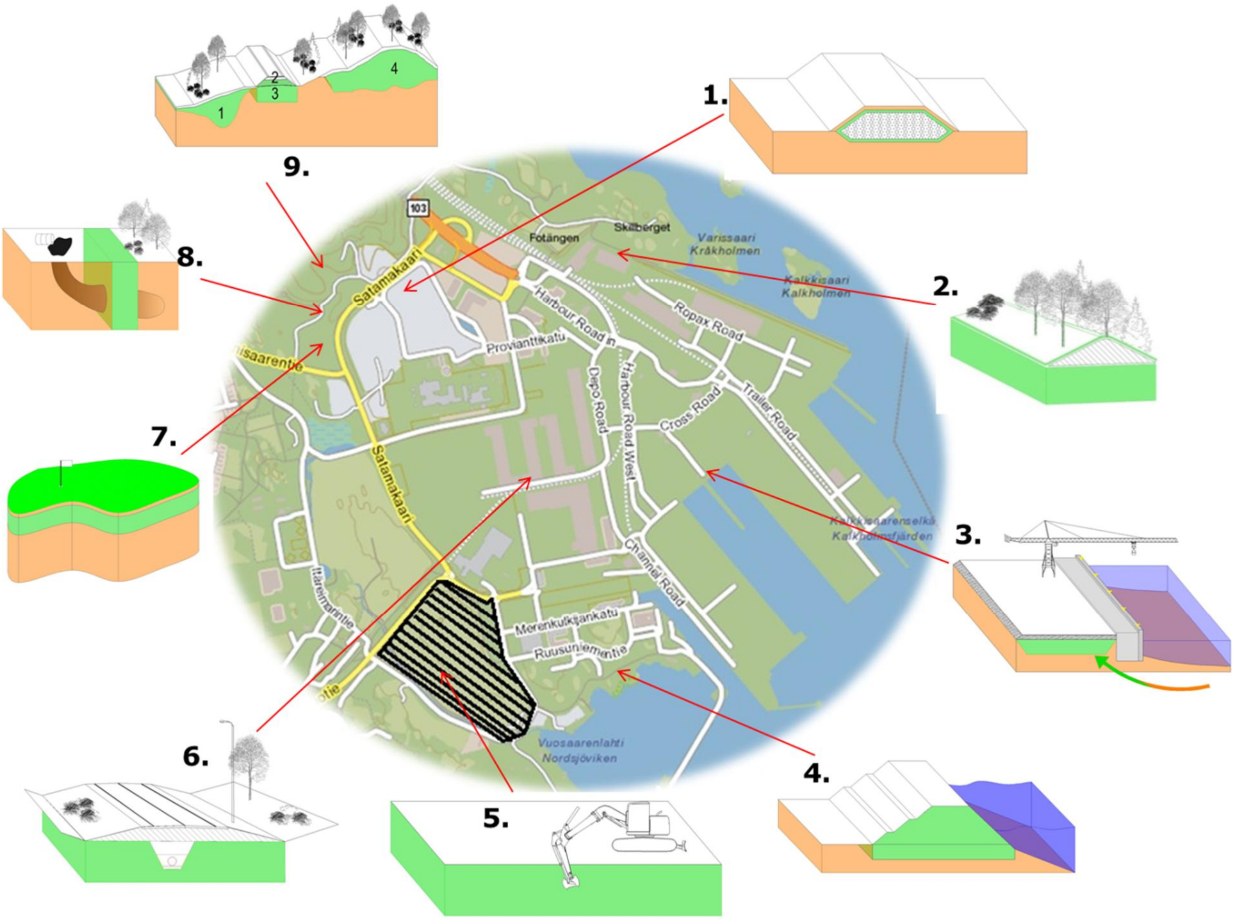


Figure 6.1 Mass stabilization applications in big regional building projects: 1. compaction structures, 2. noise barriers, 3. port structures, 4. flood barriers, 5. pre-construction, 6. road, streets and municipal engineering, 7. utilizing contaminated soils, 8. environmental protection structures and 9. landscaping

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.

No processing of surplus soft soils Soft soils processed into construction material

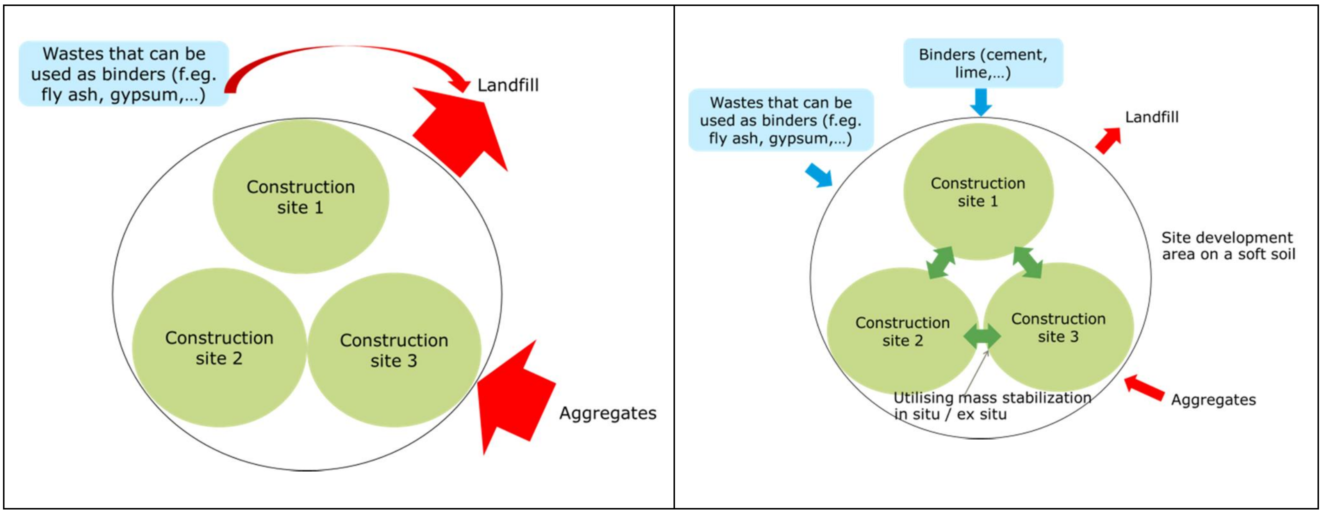


Figure 6.2 Utilizing low-quality surplus soft soils in regional building projects: a) "Traditional" procedure, where low-quality soils are transported to landfill, and b) Optimized procedure, where low-quality soils are processed into earth construction material.

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.

Table 6.1 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

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.

7.7 Laboratory test methods

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

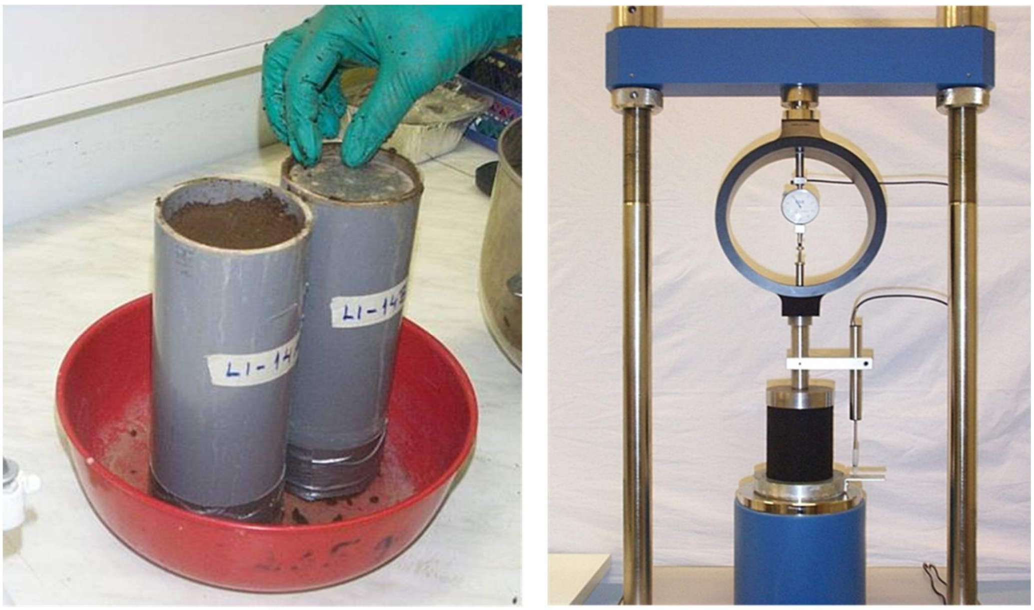
On the basis of drilling and laboratory tests results, it is attempted to initially outline the quality of the soil masses to be stabilized including variations of quality in the target site, as in particular to evaluate the stabilization potential bearing in mind the target's most challenging areas 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. STAGES OF THE MASS STABILIZATION PROJECT

The main stages of the mass stabilisation project implementation and its progress can be depicted in the way which is presented in Figure 8.1. 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 8.2 illustrates how the mass stabilization project stages progress with time.

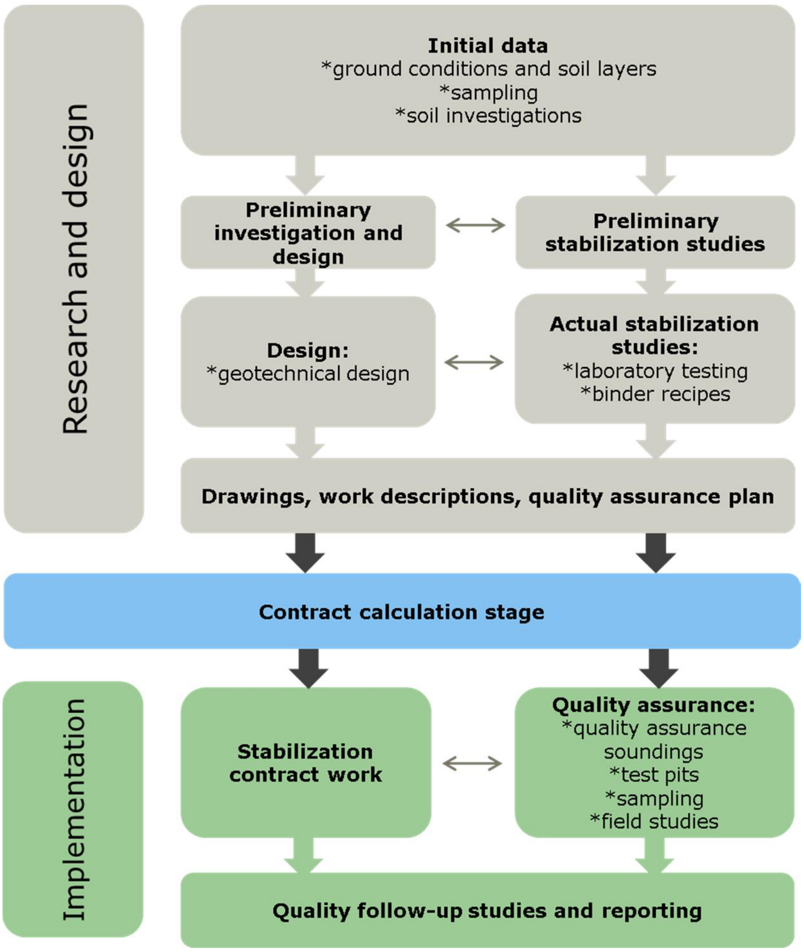


Figure 8.1 The main stages of the mass stabilization project. In some cases, it is possible to progress straight from the preliminary planning stage to the implementation stage. Documented experience of prior deep stabilization carried out in the site or the adjacent area constitutes a prerequisite to such a progress.

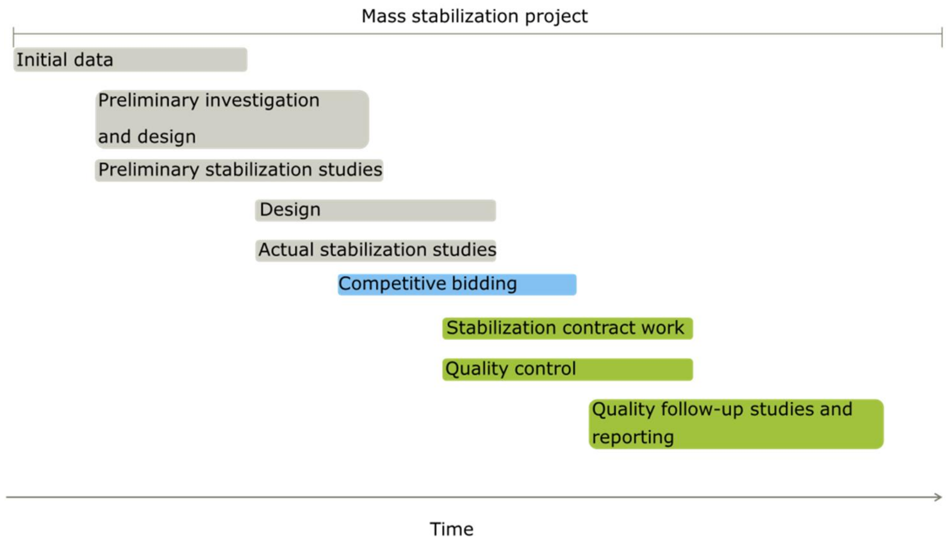


Figure 8.2 The principle of placing mass stabilization project tasks on the time axis.

9. DESIGNING MASS STABILIZATION

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

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

10. CONSTRUCTION

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

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.