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Regional Report: European Practice of Soil Mixing Technology

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ABSTRACT: Europe has a diverse topographic, social and economic structure. The geological and geotechnical setting is complex, with difficult geotechnical conditions in many urbanized areas. The geological and geotechnical conditions in European countries are described. The evolution and recent developments of deep and shallow soil mixing methods are presented, covering dry and wet mixing methods. The practical application of deep and shallow mixing is discussed. Based on the European standard on deep mixing, prEN 14679, design and execution aspects are addressed and illustrated by examples. The activities of European organizations and regulatory agencies, which are of relevance for the execution of deep mixing, are listed. An overview of the geo-hazards in the European region, for the mitigation of which deep mixing could be applied, is given. Recent conferences and the RTD activities of organizations, institutions and authorities are summarized. An overview is given of typical deep mixing applications in Europe. Finally, market shares of soil mixing methods and future RTD needs are addressed.

1 INTRODUCTION

1.1 European Setting

Europe comprises a diversity of geographic, topographic and urbanized regions, with large natural, technical and cultural resources. Powerful metropolitan areas are the major source for industrial and technical development. The diversity of rural regions, coastal areas, islands and mountains offer a multitude of opportunities for growth and development. The distance from the northernmost to the southernmost point is 4 250 km and the east-west extension is 5 500 km, Fig. 1.

Fig. 1. Topographical map of Europe, compiled from www.google.com.

Europe has, compared to its surface area, a very long coast line, longer than any other continent. About one third of the surface area consists of islands and peninsulas, such as Iceland, Ireland, and the British islands, Scandinavia, Italy or Greece. Many of these coastal zones are densely populated, and in particular in the vicinity of estuaries. Europe is the second smallest - but the second most densely populated – continent, with over 730 million inhabitants (1999). About 70 % of the population lives in urban areas which are located in central Europe and concentrated in southern England, Belgium, The Netherlands, Luxemburg, Germany and Northern Italy, Fig. 2.

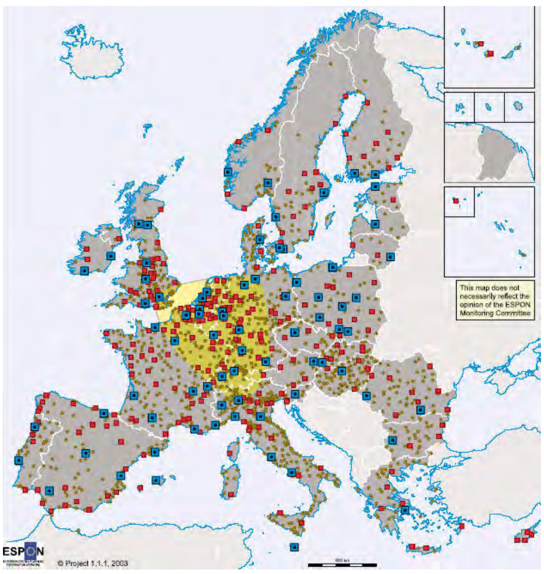


Fig. 2. European growth areas according to EU study, ESPON Project 1.3.1 (2004).

In the Mediterranean countries the urban areas are concentrated along the coastlines and are often associated with the tourism industry. This makes Europe one of the most urbanised continents in the world

1.2 The European Union

The European Union (EU) of soon 27 countries will provide the living space for approximately 500 million people, covering over 4 million km^2 of land. The enlarged EU has, seen from a European perspective, a dominant core area - the "Pentagon" shaped by London, Paris, Munich, Milan and Hamburg, cf. Fig. 2. This region has a well-developed infrastructure. Around 40 % of the population lives in this core area, which covers only 20 % of the territory, but accounts for 50 % of GDP per year within the EU. Future growth and prosperity rely on efficient transport and communication networks and global connections. However, a number of other regions are facing problems due to historic reasons, geographical features, demographic development and a fragile environment. Also there the potential for future growth is very high.

1.3 Challenges for the Geotechnical Profession

Europe covers an area, which is diverse in terms of geology, topography and distribution of urban and rural areas. Europe is a highly industrialized region, the wealth and future growth of which depends to a significant degree on an efficient construction industry. However, decreasing land resources, intensified urbanization and development of marginal land offer new challenges to planners and engineers. Industrial and sociological development requires reliable energy supply and an efficient distribution infrastructure.

At the heart of social and industrial growth are the development and safe operation of a modern transportation infrastructure (railways, highways, sea ports and airports), and an efficient communication network. However, the mounting pressure due to urban expansion has a negative environmental impact. Examples are change of groundwater regime, release of contaminants to surface and ground water, increased level of noise and vibrations etc.

A challenge for the geotechnical profession is to supply efficient but also environmentally-friendly construction techniques, to reduce the consumption of natural resources and to promote the use of less harmful products. The construction industry - and to a high degree the foundation industry – can play an important role in this effort.

For many of construction projects, cost-effective ground improvement methods are important. Specific foundation methods are used in different regions, based on geological settings, tradition, climate considerations and experience of the local construction industry. This aspect has been recognized by the EU, which is funding several research and development projects. An important goal has been the establishment of thematic networks, embracing all participants of the construction industry, such as governmental bodies, contractors and material suppliers, consultants and researchers as well as standardization institutes and other professional organizations. At the same time, the EU is introducing new regulations which have the aim to harmonize design by standardization and to assure safe and environmentally-friendly project execution at an adequate quality level. These developments will affect the foundation industry in the EU and the future application and potential marked of ground improvement methods, including soil mixing.

2 GEOLOGY OF EUROPE

2.1 Geological Conditions

Europe has a complex geology, Fig. 3. The oldest geological regions are found in the north-eastern part of Europe, which is dominated by the Fennoscandian (or Baltic) shield which includes Norway, Finland and the north-western part of Russia. Most of Scandinavia is covered by moraine. Glacial erosion has reshaped the surface layers of Scandinavia and the northern areas of central Europe and the British islands, with glacial and post-glacial deposits in valleys and depressions. Deep fjords towards the west and an extensive archipelago, with numerous small islands towards the east, characterize the coastal regions of Northern Europe.

Fig. 3. Geological map of Europe. Published with the permission of BGR. Copyright BGR, (Asch, 2004).

The flat areas of the Scandinavian and Baltic region, the Kola peninsular and Karelia were exposed to glacial erosion and are characterized by numerous lakes. The flat areas of southern Sweden and most of Denmark belong geologically to the Central and Western European morphological zone, characterized by moraine deposits and glacial river beds, filled with post-glacial deposits. The central and northern areas of Europe are drained by large rivers, flowing in shallow valleys, such as the

Wisla, Elbe and Rhine. Towards the south dominate moderately high mountains, plateaus and rolling hills. In the west, several large basins (London-, Aquitaine- and Paris basin) are drained by large rivers, such as the Thames, Garonne, Loire and Seine. Ridges of sedimentary rock (Cuesta landscape) form undulating landscapes, which are typical for the London and Paris basin as well as in southern Germany. The Central Massive is located to the east of the Aquitaine basin, with extinct volcanoes and carstic lime stone regions.

The eastern flat lands from the Baltic to the Ural mountain range are the largest flat areas of Europe, usually with elevation below 200 m high. The northern plateaus are characterized by moraine and ice-age deposits, while the southern regions are dominated by eolian (loss) soils. Large rivers drain these areas towards the north and the south. The Caucasus mountain range and the Caspian Sea create the southern boundaries, while the Ural mountain range defines the eastern boundary.

The central European region is dominated by the Alps and the Alpine Foreland. The Bohemian mountain range to the east changes gradually into the Carpathian Mountains. The river Rhine and its tributaries drain the Alpine Foreland towards the north, along occasionally deep valleys. The Alpine region was glaciated and is characterized by U-valleys, lakes and major moraine deposit. At the eastern boundary of the Alps is located the Vienna basin, which was formed during the tertiary period. It is composed of deep sedimentary deposits of dense gravel, sands and stiff clays and marl (Wiener Tegel). The basin continues towards the east into the Hungarian and Romanian low lands. The central European region is drained towards the east by the Danube River and its tributaries.

Southern Europe consists of three major peninsulas and a large number of larger and smaller islands. The Iberian Peninsula is to a large extent a high plateau, which is limited to the north by a mountain range (Pyrenees). Low lands are found along the major rivers. The Apennine peninsular is dominated by a north-south oriented mountain range. The river Po flows from west to east across northern Italy and passes through many major Italian cities. The estuary creates a wide delta region with many channels. In the southern part if Italy several active volcanoes (Etna, Stromboli) are located. Also the Balkan region is mountainous with extensive carstic regions. The southern and eastern European region is a highly active seismic zone. The Mediterranean coast line is very variable, with several large mountainous islands (Crete, Malta, Sicily, Corsica and Sardinia). Iceland and the Faroe Islands are of recent volcanic origin where basalt has formed large plateaus. Central Iceland is an active volcanic region with a large glacier in the southeast. Large sand deposits exist along the southern coast.

3 GEOTECHNICAL CONDITIONS

3.1 General

The climatic changes during the Quarternary period have influenced the geological and geotechnical conditions of today. In particular, the most recent glacial period, which ended about 10 000 years ago, has had a fundamental impact on the geological and geotechnical conditions in Europe. The northern hemisphere and the Alpine region were then covered by 2 – 3 km of ice. As a result of the action of the advancing glaciers the surface was reshaped and soil transported over large distances, creating different types of moraines. Moraine deposits can be found in all areas which have been covered by glaciers. Their granular composition can vary considerably but moraine deposits are usually dense and overconsolidated. Early Holocene conditions seem to have been slightly warmer than at present, peaking around 8,000-5,000 years across central and northern Europe. During the glacial and post-glacial period, glacial rivers transported large quantities of sediments towards the cost, where they were deposited as very loose sands, silts and clays. Eskers are an important geological feature, which can cause significant geotechnical problems, Fig. 4. Eskers are only found in areas that were once glaciated. Because they were created by glacial meltwater they tend to meander across the surface and may resemble the drainage patterns of rivers and streams of today.

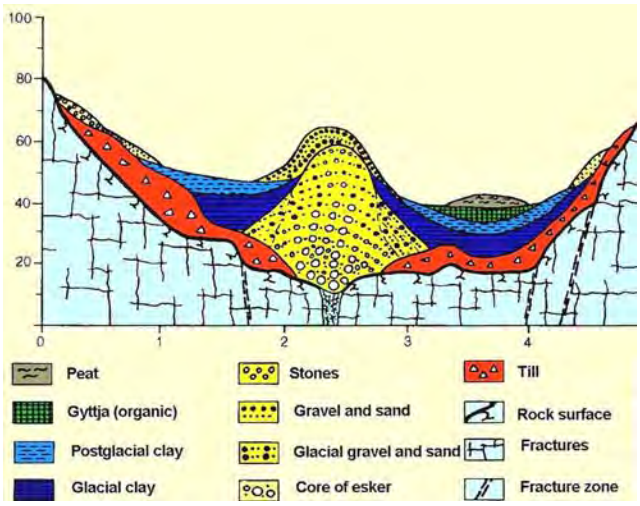


Fig. 4. Typical cross section of an esker.

Soft clays and loose sands are usually found below the highest coast line of the last glacial period. In many estuaries of large rivers, sedimentation is still going on and resulting in the deposition of deep deposits of silty and clayey soils. These soils have usually a high compressibility and low strength, thus posing formidable challenges to geotechnical and foundation engineers. The following summary of the geotechnical conditions in Europe can only cover the main geotechnical features, and in particular as these relate to deep soil mixing applications.

3.2 Austria

The major part of Austrian territory is dominated by mountains, which are oriented in the west-east direction. At their eastern boundary, near Vienna, the mountain range continues towards the northeast in the Carpathians. The northern and north-western parts of the country are occupied by the southern margins of the Bohemian Massif. Two prominent lowlands are the Vienna and the Styrian basin. Quarternary deposits are the most important foundation soils. During the last glaciation, the Alps were covered by ice which shaped the valleys and Alpine foreland. Glacio-fluvial sediments are common in alpine valleys, such as gravels, sands, silts and clays. In the non-glaciated foreland, rivers deposited soils in the form of terraces, for instance in the Vienna basin. In some areas, loess and loam was deposited on top of the older terraces.

3.3 Baltic Countries

The territory belongs to the East European Plain. Quarternary deposits cover the whole territory, most of them originating from activities of the Scandinavian glaciation. More than half of the territory is covered by glacial till, about 20% by sand. About 5 % is covered by swamps.

3.4 Belgium

The country is rather flat with a continuous transition from a plain at the North Sea and the Dutch boarder to the highlands in the south. The northern part of Belgium is constituted of secondary, tertiary and Quarternary formations slightly banded to the north. Bedrock is covered by alternating layers of Tertiary clay, sand and gravel sediments with thicknesses up to hundreds of meters. The Pleistocene formations have been influenced by glacial periods, giving rise to formation of marine, coastal, river, lake and wind deposits of sand, clay, peat and loess. Holocene erosion and river sedimentation have further altered the subsurface, especially in estuaries.

The soil deposits of northern Belgium are essentially constituted of sands and clays, which are loose formations, similar with the formations existing in the Netherlands. The deposits of the alluvial and the terraces of the river Meuse, Sambre and Scheldt and some of their tributaries are constituted of fluvial silts and peat resting sometimes on a thick layer of gravel.

3.5 Bulgaria

In Bulgaria, soft soils are encountered mainly along the Black Sea and the Danube river. In many cases these soils are very soft weak and create difficult foundation conditions

3.6 Czechia and Slovakia

The geo-morphological conditions are characterized by a great variety of soil types. About 4/5 of the country is rolling countryside with valleys and rivers. Bedrock is found often quite near to the surface. The river deposits are predominantly coarse-grained. Only in some broad valleys in local tectonic basins these are filled with tertiary and Quarternary deposits of fine materials. Recent construction activities have started to take place in these previously rural areas. Tertiary deposits are composed mainly of clays, silts and sands with interbedded gravels. These older deposits are covered with eolian deposits, loess, slope deposits, such as clayey and loamy soils, fluvial deposits and glacio-fluvial deposits of gravel, sand, loams and clays.

3.7 Denmark

Denmark is a lowland area, on average not higher than 30 m above sea level. The extreme limit of the Scandinavian ice shield during the last glaciation is clearly marked, with the contrast of between the flat regions towards the west (mainly sands and gravels) and the loamy hills of eastern and northern Denmark. Marine deposits of sand and gravel can be found around the Limfjord in the north.

3.8 Finland and Karelia Region

The soils prevailing in Finland were for the most part formed during the last Ice age. Due to this, the most frequently encountered soils are moraines containing stones and boulders. Moraine covers almost 80% of the surface area, which overlays Precambrian rock. The moraine soils are only a few meters thick and predominantly sandy, but can contain blocks and boulders of granite. Besides this, clay and silt as well as sand and gravel are found. About one third of Finland’s surface is covered by peat.

As the glaciers melted, glacial river deposits and shore sand deposits were formed. After the melting of the glaciers; fine-grained sediments settled in the Baltic Sea; first in the form of varved silts and later on clays and organic clays. During the humid periods in the recent past, extensive swamps led to the development of peaty soils.

Coarse grained soils are found mainly in eskers, deltas and shore deposits. The gravel deposits are often stony. Fine-grained soils are primarily found in the coastal regions, where they are for the most part very soft. Clays can be organic and silty soils are found more in the inner parts of the country. The average thickness is about 10 m, but can increase to 50 m in valleys along the coastal region.

3.9 France

Approximately 10 % of the area of France is covered by sedimentary deposits. Many regions such as the Mediterranean coastline, the Massif Central or the Pyrenees and to a large extent the Alps consist essentially of Palaeozoic zones and metamorphic or crystalline rock formations. In most cases these zones are covered by residual soils, which were created due to weathering. Two large sedimentary basins (Paris and Aquitaine) are covered with secondary formations. Two main river valleys (Rhone-Saone and Rhine) are filled with sediments from neighbouring mountains. In numerous smaller river valleys and coastal plains, which are mostly covered with Quarternary sediments, soft clays, sands and gravels, as well as peat can be found.

The tertiary and Quarternary deposits are the most important areas foundations of civil engineering structures. The two main types of soils found in France are eolian sands in the form of dunes along the Mediterranean, Atlantic and Channel coasts. Marine sands can be found both on recent shore deposits as well as in tertiary deposits such as the Paris basin. Fluvial sands and gravels are frequent in the main river valleys, often in the form of terraces. Clayey muds and soft organic clays can be found on the Mediterranean and Atlantic coasts and in the valleys of main rivers.

3.10 Germany

In the northern part of Germany, the Holocene subsoils consist of marine and fluvial sediments with different organic material, often of low density. Below these typically 5 m thick sediments, follow Pleistocene layers, which have been preloaded by the Scandinavian glaciers, thus having higher density and strength.

Large areas in the south and southwest are occupied by consolidated hard rocks. Some fluvial and limnal sediments are problem soils. Also in central, western and southern Germany are large areas which developed during glacial and periglacial conditions (for instance as a result of Alpine glaciers). The often more than 20 m thick glacial terrace deposits (mostly sand and gravel) extend beyond existing river channels. In the mountainous regions, numerous Pleistocene strata can be found, consisting of unconsolidated sediments.

Quarternary Holocene deposits consist primarily of dune, beach or marine sands and/or gravels. Sandy or clayey river terrace deposits exist in coastal areas and river valleys, in part with organic intercalations. Marsh areas can also contain alluvial loess, peat and gyttja. Quarternary Pleistocene soils consist of till, glacial basin clay, loess and loess loam, sand and gravel

3.11 Hungary

Hungary occupies the central part of the intermountain basin of the Alpine belt of Europe – the Carpathian basin. The Hungarian central mountains are flanked by two plains. The little plain has a basement of Palaeozoic sediments. The surface is covered by Holocene and Pleistocene fluvial sediments, mainly gravel and coarse sand, which are exposed over large areas. The great Hungarian plain is filled with Quarternary deposits. This region is characterized by sandy – silty hills rising above the mean elevation. Some parts of the plain are covered by thick loess deposits. The Trans-Danubian Tableland is composed of late tertiary deposits which are covered by a thin layer of loess.

3.12 Ireland

The coastline is formed of strong older igneous and metamorphic rocks. The engineering geology is dominated by a mantle of 10 to 15 thousand year old glacial till and glacial sand and gravel, cobble and boulder. These soils are usually medium dense to dense or stiff to very stiff in consistency. Later alluvial activity has covered the glacial deposits with soft clays, silts and peats in some low lying areas and along river flood plains.

3.13 Italy

The Mediterranean area is geologically young and very complex. Pleistocene marine transgression led to the deposition of fine marine sediments in shallow areas. The territory consists mainly of mountains and hills, while flat land areas cover less than 25 %. These land areas are located mainly along the Adriatic Sea, the most important being the Padana (Po) Valley. In the alluvial flat lands and hills, thick layers of medium grained and fine-grained deposits are encountered.

3.14 Netherlands

Geologically, the Netherlands is a delta area. Geotechnically, a distinction can be made between the western part (Holland) and the remaining areas. In Holland, extensive areas with up to 20 m thick Holocene clay and peat layers are present, overlying sands. These layers are soft and have low strength. In the centre, east and south of the Netherlands, structures can normally be founded directly on Pleistocene and Tertiary sand layers.

The Dutch sector of the North Sea includes major oil and gas fields. The soil conditions are dominated by Pleistocene sands and clays. The sands are typically very dense and the clays are very stiff.

3.15 Norway

Only 25% of the land area is covered by soil deposits. The major part is either bedrock or a very thin cover of moraine on bedrock. Areas covered by deep soil deposits are particularly concentrated to lowlands, in the bottom of valleys and along a narrow strip along parts of the coast line. Following the most recent glaciation, about 10 000 years ago, large rivers deposited the transported material into the sea. The sea level was significantly higher than at present. Below the marine boundary, glacio-fluvial deltas have been formed, mainly containing gravel and sand. Clays and silts were deposited in the sea and these soils dominate. The silty clays and clays have in some areas very low strength and high sensitivity.

3.16 Poland

The major part of Poland is composed of lowlands. The thickness of the Quarternary deposits can be as large as 300 m. Geological processes related to glaciations made most of Polish soils overconsolidated. Only the deposits formed due to sedimentation processes after the last glaciation are normally consolidated.

3.17 Romania

With the exception of mountain areas, Quarternary deposits are of greatest importance. In terraces and alluvial deposits, normally and slightly overconsolidated clays, medium dense and dense sands and gravels are found. Special problems are caused by silt-type collapsible soils (loess), which occur mostly in the plains and plateau zones. Unconsolidated recent alluvial deposits exist in the lower course of rivers and along the Danube.

3.18 Russia

The Urals form the conventional geographic boundary between the European and Siberian parts of Russia. Russia's dominant relief features are (from west to east) the East European plain, the Urals, the West Siberian lowland, and the central Siberian plateau. In the south-east of the European part of Russia, deposits of the Quarternary period dominate. These are predominantly of glacial origin. In the north-east, permafrost governs the geotechnical conditions. Principal soils of glacial origin are moraine clay and silty clay, fluvio-glacial sands and gravels; lake-glacial deposits (varved silty clays and silty sands). These soils have often low strength and stiffness. Besides the soils of glacial origin, eroded and residual soils as well as various alluvial deposits (laminated clay and sand) of great thickness occur. Quarternary soils can have variable strength and stiffness.

3.19 Slovenia

Geo-tectonically, Slovenia belongs mainly to the southern Alpine region and the Pannonian basin. Due to the complex geology, geotechnical conditions can be very variable and demanding. Soft soils have been deposited since the Pleistocene and are usually fine-grained, of variable plasticity and mostly normally consolidated. In some marsh areas, peat and organic soils can be found. The most significant areas are the Ljubljana marshlands and the hinterland of the Adriatic coast. The total thickness of the Pleistocene fluvial and marsh sediments can be up to 150 m, while the very soft upper layers are typically less than 20 m thick. The coastal region of Slovenia, as well as the north-western part of Croatian Istria is covered by very soft marine and fluvial clays.

3.20 Spain

The Quarternary period has determined the soil formation. Soft soils occur mainly in continental-marine transition areas, such as coastal plains near river estuaries, deltas and lagoons. Soft sediments are developed in the delta of the river Ebro. In mountain areas of Northern Spain and at higher elevations in mountainous areas of the south, peat bogs are occasionally found.

3.21 Sweden

The geotechnical conditions were strongly influenced by the last glaciation, which started to retreat from southern Sweden about 14 000 years ago. In connection with the retreat of the ice, Sweden was covered alternating by fresh and brackish water. The highest water level – the highest shoreline – was affected by the elastic rebound of the depressed crust of the Baltic shield. The soils are geologically young and belong mainly to the Quarternary period. The soils were formed by the movements and the melting of the last land ice and subsequent processes. The glacial soils are mainly tills (moraine) and glacial sediments. Till covers about 75% of the land area. The glacial sediments consist of sand, gravel and boulders in the form of eskers and deltas, and fine-grained sediments (clay and silt) deposited outside the edge of the ice. Post-glacial soils (silts and clays) are normally found overlying glacial clay. After the glacial period, organic material became mixed with the fine-grained material, forming gyttja and organic clay. Peat bogs were formed in many areas.

3.22 Switzerland

The most recent ice age formed most of the soils of geotechnical importance. In the central areas adjacent to the Alpine region, moraines consist mostly of overconsolidated and compact sandy and clayey silts with varying amounts of boulders and gravel. In rive areas, as well as near existing and former alpine lakes, the soil conditions can be very heterogeneous, including fluvio-glacial deposits of boulders and gravel, as well as normally consolidated soft deposits of alternating layers of peat, clays, silts and sands or gravels. Difficult geotechnical conditions are encountered in areas with normally consolidated soft post-glacial lacustrine clays, silts and fine sands, which can exhibit high sensitivity.

3.23 United Kingdom

Natural deposits formed prior to the Pleistocene glaciation are generally referred to as rocks. The strength of these formations can vary such that some of them are classified as soils. These include many of the deposits in the south east of the United Kingdom, such as the London clay and the Gault clay. Most of the UK has been affected by glaciation which has resulted in extensive drift deposits of till (boulder clay), laminated clays and other glacial materials as far south as London. Periglacial and lacustrine deposits are also found in plains and valleys together with estuarine and coastal muds and silts. Peat and other organic soils are found throughout the upland region. Drift deposits in the upland region are predominantly firm and stiff to hard gravelly sandy clay containing boulders, lenses of sand and gravel. The more recent deposits comprise softer organic and alluvial clays and loose sands

4 SOIL MIXING METHODS

4.1 Introduction

Due to the variable geotechnical conditions in Europe, different soil mixing methods have been developed in different countries. Deep soil mixing is presently most common in regions with deep deposits of soft, compressible clays or loose sands with low strength. However, deep mixing methods can be applied in a variety of soil conditions and are gaining increasing use in Central Europe as well. An important advantage of deep mixing is that the methods can be adapted to specific project requirements and site conditions. The following section gives an overview of soil mixing methods and their development in Europe.

4.2 Classification of Soil Mixing Methods

Deep mixing can be classified with regard to the method of mixing (wet/dry, rotary/jet-based, auger-based or blade based) or the type of binder being used (dry or wet).

In dry mixing, the binder is a powder, normally a mixture of cement and dehydrated (unslaked) lime. However, the binder can also consist of a mixture of cement, lime, gypsum, blast furnace slag or pulverised fuel ash (PFA) in granular or powdered form. Air is used to feed (or incorporate) the binder into the soil. In wet mixing the most common binder is cement, but different additives are also used. The binders are injected into the soil in dry or slurry form through hollow rotating mixing shafts tipped with various cutting tools.

Soil mixing methods can be subdivided into two general categories: deep mixing and shallow mixing. Both methods include a variety of proprietary systems. The European Standard on Deep Mixing, prEN 14679, covers mixing by rotating mechanical mixing tools, where the lateral support provided to the surrounding soil is not removed and where treatment is executed to a minimum depth of 3 m. Currently, deep mixing is limited to treatment depth of about 30 m

Shallow mixing was developed to improve soft and compressible soft, but also dredged sediments and waste deposits. The treatment depth is limited to a few meters. Shallow mixing is also a suitable method for in situ remediation of contaminated soils and sludges. In such applications, the soils have to be thoroughly mixed in situ with an appropriate amount of wet or dry binders to ensure stabilisation of the entire volume of treated material.

4.3 Historic Development of Deep Mixing

In the following, a brief historical review of the development of soil mixing is given. Probably one of the earliest European innovations to improve and/or seal the native soil by means of mixing in situ with cementitious grout was submitted in Poland on 22.12.1966, and awarded a national patent No. 55511 on 12.06.1968, Fig. 5.

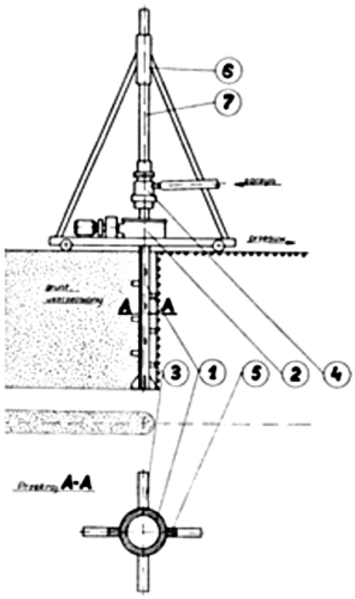


Fig. 5. Polish Patent No 55511 from 22.12.1966, describing a new method of soil improvement and sealing.

The grout was injected from the tip of a mechanical mixer consisting of a simple drilling head and separated horizontal blades. Unfortunately, there were no practical applications of this novel system at that time.

In Sweden, research and field trials using dehydrated (unslaked) lime started in the mid 1960s. Since 1975, lime and later lime-cement columns have been used for commercial ground improvement projects. A mixture of dry cement and lime binder is introduced pneumatically in the soil, using different types of rotary mixing tools, Fig. 6.

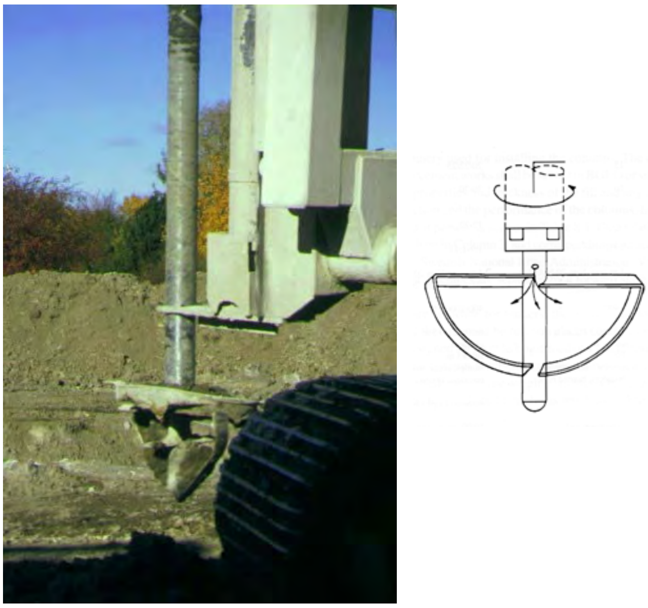


Fig. 6. Mixing tool of Swedish dry mixing method.

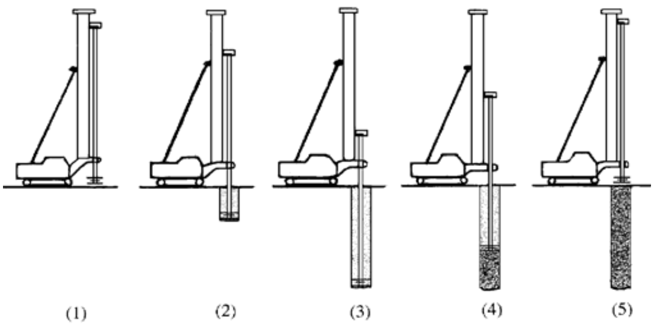
Wet mixing, using cement slurry as a binder, originated in Japan in the middle of the 1970’s and has thereafter been used in Europe. In Central Europe, the earliest wet deep mixing activities took place in Germany, France and Italy in the late 1970s and early 1980s. The development and initial trials of Bauer’s Mixed-in-Place (MIP) system started in 1977 (Stocker and Seidel, 2005), Fig. 7. The original idea was to install vertical walls in the ground for soil nailing works in order to avoid shotcrete cover. The MIP panels were constructed using four closely mounted continuous flight augers of ca 0.2 m diameter, arranged in a row.

The first commercial application of the MIP method utilising single shafted crane and wet binder took place in Nürnberg in 1987. MIP piles were executed to create panels of mixed soil filling-up a “Berliner Verbau”-type temporary retaining wall constructed in sands. Subsequently, a more advanced triple auger wet mixing system has been developed since the early 1990s. It is comprised of three closely spaced, non-interlocking, full length augers, arranged in a row and driven as a coupled pair and counter rotating single auger. This system has been in use since 1994, primarily for construction of temporary and permanent panels supporting excavations, cut-off walls, ground improvement, and environmental purposes (Ausserlechner et al., 2003).

Fig. 7. The first application of Mixed-in-place (MIP) piles, (Stocker and Seidel, 2005).

4.4 Dry Deep Mixing Method

By the dry deep mixing, columns with a diameter of 0.5 to 1.2 meter can be manufactured to a depth of normally 15 to 25 meters. The mixing and monitoring process has been improved gradually and is today executed using electronic process control systems. The installation is carried out according to the following procedure, from left to right, Fig. 8.



1) the mixing tool is correctly positioned; 2) the mixing shaft penetrates to the desired depth of treatment with simultaneous disaggregation of the soil by the mixing tool; 3) after reaching the desired depth, the shaft is withdrawn and at the same time, the binder in granular or powder form is injected into the soil; 4) the mixing tool rotates in the horizontal plane and mixes the soil and the binder; 5) completion of the treated column.

Fig. 8. Sequence of installation by Dry Deep Mixing.

In Sweden, dry deep mixing, initially also known as the “lime column method” (because initially, lime only was used as binder), has been applied commercially since the mid 70-ies, mainly for the support of highway and railway embankments on soft, compressible clays. The first commercial project with lime-cement column method in Finland took place in 1988 and in Norway in 1990. Today, the method is referred to as the Nordic Dry Deep Mixing Method (Holm, 2003). The lime-cement column method is mainly used in soft clays but also in organic clays and clayey silts. In the Nordic countries, about 3 to 4 millions linear metres of lime-cement columns are installed annually, especially for infrastructure projects. A modern lime-cement column machine with mixing vessel for supply of cement and lime is shown in Fig. 9.

Fig. 9. Deep dry mixing equipment, mixing tool and base machine with containers for supply of binder (cement and lime).

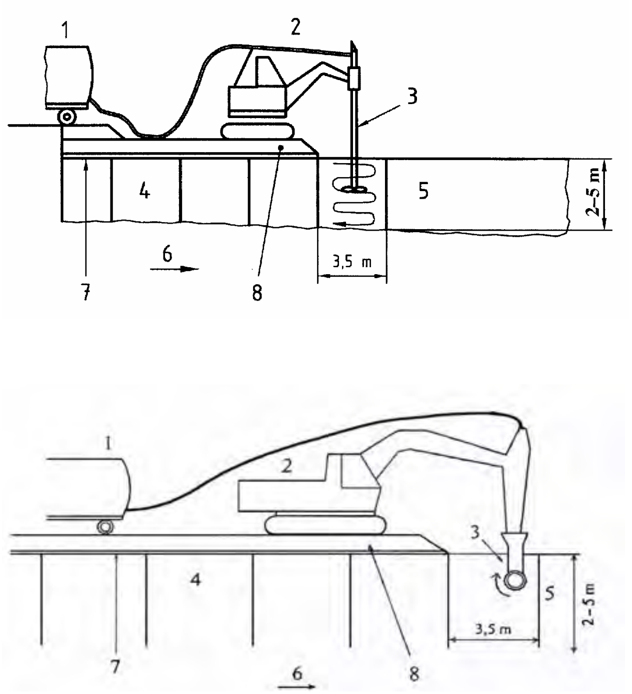
With an increasing number of proven applications, especially since 1989, this method had become the predominant method of ground improvement in the Nordic countries. The amount of binder required to stabilize the soil can vary considerably, depending on the soil conditions and the project requirements. The amount of binder ranges typically between 80 and 200 kg/m^3 of stabilized soil. Normally, a mixture of 50 % lime and 50 % cement is used. The strength of the stabilized soil is typically 100 to 200 kPa. The stabilization ratio (stabilized soil/unimproved soil) is generally 10 to 30 %, thus significantly lower than for instance in Japan, where the ratio if around 50 %.

At present, dry mixing is used mainly in the Nordic countries (Finland, Norway and Sweden), but some projects have been also carried out by Swedish contractors in other countries, such as Poland (first in 1995) and the United Kingdom (first in 2001). Field trials were also conducted in the Netherlands and Germany. In Poland the major application so far of the dry method was for the new city carriageway in Szczecin, involving more than 555,000 lin. m of cement/lime columns.

4.5 Dry Shallow Mixing

Improvement of superficial soft soils by dry shallow mixing is known as “mass stabilisation”. It can be carried out with conventional lime-cement column equipment or by purpose-built machines. Laterally overlapping columns are created with upward and downward movements of one or several rotating mixing tools. This method is most cost-effective when using large-diameter mixing augers or multiple shaft arrangements, as practiced for example in the USA.

More recently, another method of mass stabilisation has been developed in Finland. The Finish Road Administration initiated in 1992 a research project with the objective to develop a suitable and economical method of peat stabilisation. The base machine is a conventional excavator, equipped with a mass stabilisation mixer. The binder is fed to the mixing head while the mixer rotates and simultaneously moves vertically and horizontally within the stabilised soil block, as shown in Fig. 10.



1 Stabiliser tank + scales; 2 Execution machine; 3 Mixing tool; 4 Mass stabilised peat, gyttja or clay; 5 Peat, gyttja, clay; 6 Direction of mass stabilisation; 7 Geotextile (reinforcement); 8 Preloading embankment.

Fig. 10. Two methods of mass stabilisation.

The mixing tools can have different shapes, for instance mixing/cutting heads equipped with blades rotating about a vertical or a horizontal axis. The diameter of the mixing tool is normally 600 to 800 mm, and the rotation speed lies between 80 and 100 rpm. The mixing pattern of mass stabilisation is planned taking into account site specific conditions and capabilities of the mixing machine and the mixing tool. Usual practice is to stabilise in one sequence a block of soil within the operating range of the machine, typically corresponding to 8 to 10 m² in plan and 1.5 to 3 m in depth (e.g. 2 m wide ×5 m long ×3 m deep).

The productivity rate is high, approximately 200-300 m³ of stabilised soil per shift. The amount of binder used in the Nordic countries is typically in the range of 150 to 250 kg/m³, and the targeted shear strength in peat is 50 kPa (Jelisic and Leppänen, 2003). When the prescribed amount of binder is mixed into the soil, remoulding is continued in order to obtain a homogeneous soil-binder mixture. This method can be applied in soft clays and organic soils with shear strength below about 25 kPa.

In Finland and Sweden mass stabilisation is used extensively for infrastructure projects, which require the treatment of superficial layers of peat, mud or soft clay. The first commercial application of this method in Sweden was carried out in 1995 in connection with stabilization of an embankment for Highway 601, where about 10 000 m³ of peat were treated.

Interesting applications of this method using rapid cement as a binder include the stabilisation of dredged mud deposited between embankments to create new areas for a container terminal in Port Hamina, and a park at the shoreline of Helsinki, where the deposited mud was also contaminated (Andersson et al., 2001). In Finland, also other low cost binders are used more frequently than elsewhere as substitutes for lime and cement. These substitutes include blast furnace slag, ashes, gypsum and other secondary products. These compound binders are blended in a factory, or can be mixed on the worksite.

4.6 Wet Deep Mixing

Different methods have been developed by which cement slurry can be mixed with the soil in order to create rigid columns or wall elements. These behave similar to concrete piles or concrete walls and are designed accordingly. Installation of wet-mixed columns is either carried out by means of flight auger(s) (continuous or sectional, single or multiple) or by means of blades, depending on ground conditions and applications. In reinforced soil wall structures, steel bars, steel cages or steel beams can be installed into the fresh mixed in place columns or elements. The aid of a vibrator may be required for the installation process. In wet mixing the binder is usually cement slurry. Filler (sand and additives) may be added to the slurry when necessary.

The specific quantity of slurry added can vary with depth. For machines with the outlet below the mixing tool the slurry must not be added during the retrieval phase. Whereas flight augers may be sufficient for predominantly granular soils, increasing fineness and stiffness requires more complicated mixing tools provided with mixing and cutting blades of different shapes and arrangements. The rotary drives, turning the shaft, must have enough power to destroy the matrix of the soil for intimate mixture with the slurry.

The current Bauer MIP method uses three augers with diameters ranging from 400 to 750 mm, which can be inserted and retracted vertically. The augers can be rotated clock- or anti-clockwise individually; Fig. 11. The installation is computer-controlled and various parameters are recorded in order to document and verify the execution process. The MIP method can be used for a variety of applications, such as the construction of continuous concrete walls or deep foundation elements (Stocker & Seidl, 2005).

In France, Bachy Soletanche developed the COLMIX method in the mid 1980s, in cooperation with the French Railway Authority (SNCF) and the French National Laboratory for Roads and Bridges (LCPC). The method features now twin, triple or quadruple contra-rotating and interlocking augers, generally 3 to 4 m long and driven via hollow stem rods coupled to a single rotary drive. Blended soil moves from the bottom to the top of the hole during penetration, and reverses on withdrawal ensuring very efficient soil mixing and recompaction. Several road and rail embankment stabilisation projects have been completed with this method in France, UK and Italy.

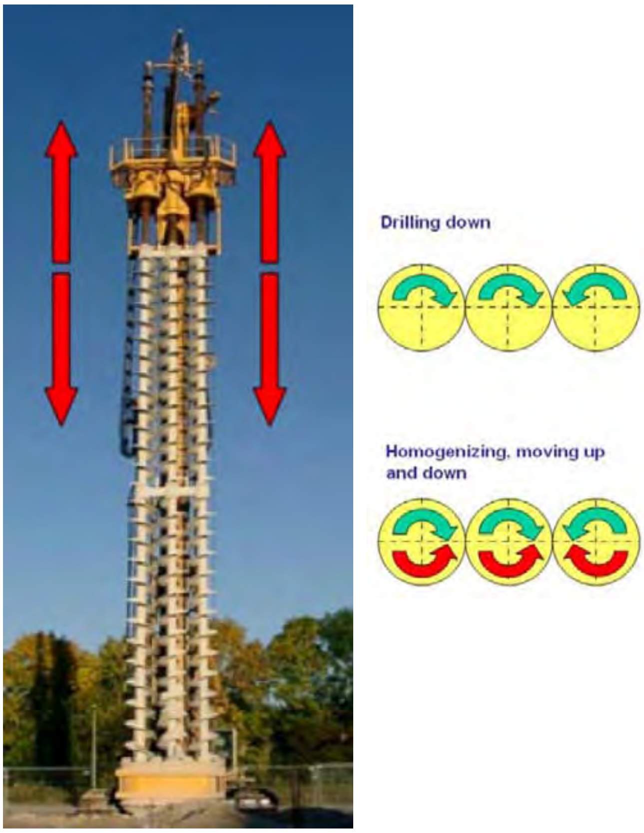


Fig. 11. Installation process of the Bauer MIP method, (Stocker & Seidel, 2005).

In Italy, Trevi SpA developed in the late 1980s a dry mixing method named TREVIMIX. The equipment has more similarities with the Japanese DJM method than with the Nordic Method. In this system one or two (more common) shafts with mixing paddles of 1.0 m (or 0.8 m) in diameter are arranged at variable spacing of 1.5 to 3.5 m and are used to disintegrate soil structure during penetration with air. Augers are then counter-rotated during withdrawal and dry binders are injected via compressed air through nozzles on shaft below mixing blades. The distinction of this system lies in its ability to operate in dry or semi-dry conditions by adding a controlled amount of water to the soil in order to ensure a hydrating reaction. First applications in Italy have been reported by Paviani and Pagotto (1991). Another development is the TURBOJET wet mixing system, which combines soil mixing and single fluid jet grouting. The system uses a tubular kelly with drilling bits and two mixing blades.

A new development by Bauer, presented also at this conference, is the Cutter Soil Mixing (CSM) system, derived from the cutter diaphragm walling technique, Fig. 12. The soil is broken down by cutter wheels rotating about a horizontal axis and mixed in situ with slurry by the rotating wheels (Fiorotto et al., 2005).

Fig. 12. Bauer CSM Cutter head (Fiorotto et al., 2005).

Another high capacity specialised wet mixing system developed in Germany in 1994 is the FMI-method (Fräs-Misch-Injektionsverfahren = cut-mix-injection). It uses a modified trench cutter, Fig. 13.

Fig. 13. Trenching machine for construction of walls by deep mixing.

The method was applied for the first time in 1996 in Giessen, Germany (Sarhan & Pampel, 1999). The FMI machine has a special cutting arm (trencher), along which cutting blades are rotated by two chain systems. The cutting arm can be inclined 80 degrees, and is dragged through the soil behind the power unit. Due to the special blade configuration, the soil is not excavated, but mixed with a binder, which is supplied in slurry form through injection pipes and outlets mounted along the cutting arm. The applications mainly covered are ground improvement works along railways and walls.

The Keller Group developed in Germany a system based on a single paddle shaft equipped with a short auger and mixing blades above the drill bit, Fig. 14.

Fig. 14. Standard deep mixing tool used by Keller.

Commercial ground improvement applications for this system have been ongoing since 1995, with complementary activities transferred in the last decade to Poland, Austria, Slovakia, Czech Republic, Italy, France, Croatia and Spain.

Currently the UK is leading Europe in the research and application of wet mixing for the containment and encapsulation of contaminated soils, including cut-off walls and reactive barriers (Al-Tabbaa and Evans, 2003). The StarNet project, which addresses different aspects of soil stabilization and solidification, is described in more detail below.

In Poland wet deep mixing was first introduced in 1999 by Keller Polska, using single axis equipment originally developed in Germany. The first project involved execution of intersecting columns forming a cut-off wall along an old dam of the Vistula River in Kraków (Topolnicki, 2003). Since then, a considerable number of DM projects have been completed, focusing on ground improvement for foundation purposes. The first worldwide applications of the deep mixing method for the foundations of 39 bridges build across and along the new A2 Motorway took place in 2002/2003 (Topolnicki, 2004), Fig. 15.

Fig. 15. Foundation for A2 motorway bridge, near Katowice, (Topolnicki, 2004).

Several innovative methods are currently under development, which uses techniques reminding of deep mixing, called “hybrid methods”. These methods combine conventional piling, grouting, jet grouting and mechanical mixing.

5 APPLICATION OF SOIL MIXING

5.1 General

Since their introduction, deep and shallow mixing methods have diversified, equipment performance has improved and processes become more complex. Electronic control and monitoring of the mixing process are today standard requirements. New binder combinations have been introduced. There is a clear trend towards an integration of different ground improvement methods, such as wet and dry mixing, jet grouting, trenching and cutting systems. As a result of significant research efforts and accumulation of well-documented, practical experience, deep mixing methods have become widely accepted in many countries.

As will be discussed below, the regulations by the EU impose restrictions on the use of construction material and the execution foundation works, which can to some extent influence or limit the use of deep mixing methods. The application of deep mixing methods is discussed in detail in the European norm for deep mixing, prEN 14679. In the following chapters, reference is made to the information given in the Annexes.

5.2 Application Areas

The use of in-situ soil mixing in Europe to improve the engineering and environmental properties of soft or contaminated ground is increasing rapidly, indicating growing interest and acceptance of this technology. The extent of applications across European countries differs considerably. Outside Scandinavia the total number of implemented projects is still small, and soil mixing is generally considered a highly specialised technology of ground improvement. However, the industrial, social and environmental developments in Europe offer major commercial opportunities for the deep mixing industry. Large development projects are taking place in densely populated metropolitan regions. Many major cities are located in coastal areas, where the tourism industry plays an important economical and social role. Land reclamation, which is important for the development of many coastal regions, is another important area where deep mixing can be applied.

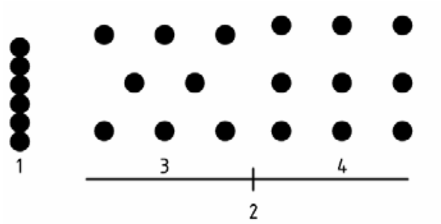
For the expansion of the transportation infrastructure, cost-effective ground improvement methods are needed, as these projects often have to be executed in areas with difficult soil conditions. Examples are highways and railways in Alpine and coastal areas, land reclamation for air and sea ports in coastal zones, marine and harbour structures for ports and harbours etc. where difficult geotechnical conditions are common.

Due to the lack of land in urban and industrial zones, construction projects must often be carried out in areas with difficult geotechnical and environmental conditions. In such situations, where stringent regulations regarding noise and vibrations are enforced, deep mixing has many advantages compared to other methods. The industrial and social expansion, tourism and the rising standard of living, create new pressures on the environment. The storage of domestic and industrial waste is a major challenge in many industrialized regions. Underground contamination or hazardous materials that can affect the execution method, the work safety or the discharge of excavation material from the site can consist of old refuse deposits, industrial waste material, chemical waste products, etc. Mixing methods can offer environmentally effective solution to this growing problem.

Some regions of Europe are particularly vulnerable to natural and man-made hazards, such as flooding, landslides and earthquakes. Also in these areas, deep mixing methods have many potential applications.

5.3 Installation Patterns

Depending on the purpose of deep mixing, a number of different patterns of column installations are used see Figures 16 to 20. If the main purpose is to reduce settlement, the columns are usually placed in an equilateral triangular or in a square pattern. If, on the other hand, the purpose is to ensure stability of, for example, cuts or embankments, the columns are usually placed in walls perpendicular to the expected failure surface, Fig 16. Overlapping of the columns is particularly important when the columns are installed for containment purposes. The stabilization is normally executed to create a block, wall and grid pattern.



1 Strip 2 Group 3 Triangular 4 Square

Fig. 16. Examples of treatment patterns in dry mixing.

Figure 17 shows the result of stabilized columns when executed in an overlapping pattern.

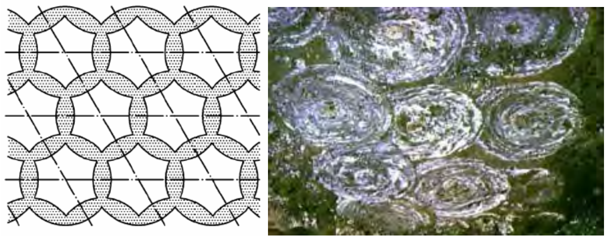
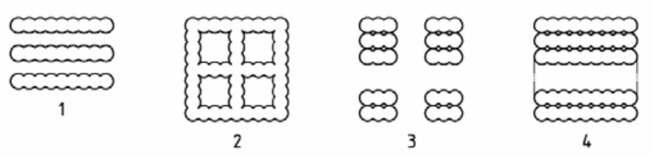


Fig. 17. Block type pattern in dry mixing with overlapping columns.

Preloading can be used as temporary surcharge in order to speed up consolidation and creep settlements during the construction period and to verify the performance of the improved soil. By monitoring the behaviour of the embankment (settlements and pore water pressure) it is possible to optimize the design and construction process.

An important aspect of this method is the flexibility in design, which can be adapted to the project-specific requirements and conditions. However, for an efficient and safe application of this concept, the active involvement of the geotechnical designer and engineer is an important prerequisite. A further and important advantage is the fact, that the method is environmentally friendly. For certain applications, such as prevention of liquefaction, dry mixing has also been used in loose granular soil.

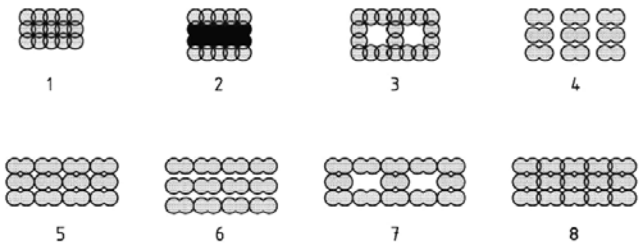
An example of the installation sequence in overlapping columns to create interlocking walls is given in Fig. 18 installing the columns in some U-formed, elliptical or circular patterns form effective barriers against horizontal actions of various kinds (earth pressure, slip surface, etc.).



1 Wall type 2 Grid type 3 Block type 4 Area type

Fig. 18. Examples of treatment patterns in wet mixing on land.

In Figures 19 different column arrangements are shown, with the aim to create cellular elements.



1 Block type 2 Wall type 3 Grid type 4 Column type
5 Tangent column 6 Tangent wall 7 Tangent grid 8 Block

Fig. 19. Examples of treatment patterns in marine conditions.

Figure 20 shows an example of interlocking elements and their installation sequence.

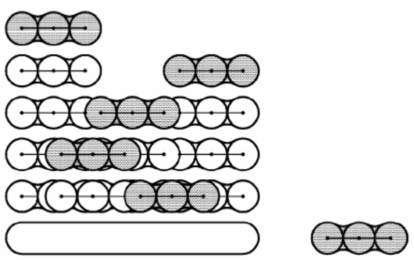


Fig. 20. Installation sequence of interlocking wall elements.

5.4 Comparison of European and Japanese Mixing Techniques

Japan is the leading country in the development and application of deep mixing methods and several European systems are based on concepts developed there.

In the following tables, different aspects of the European dry and wet mixing methods are compared with the equivalent techniques as used in Japan.

Table 1. Comparison of the Nordic and Japanese dry mixing techniques.

Equipment	**Details**	**Nordic technique**	**Japanese technique**
Mixing machine	Number of mixing shafts	1	1 to 2
	Diameter of mixing tool	0,4 m to 1,0 m	0,8 m to 1,3 m
	Maximum depth of treatment	25 m	33 m
	Position of binder outlet	The upper pair of mixing blades	Bottom of shaft and/or mixing blades (single or multiple)
	Injection pressure	Variable 400 kPa to 800 kPa	Maximum 300 kPa
Batching plant	Supplying capacity	50 kg/min to 300 kg/min	50 kg/min to 200 kg/min.

Table 2. Major capacity and execution of European and Japanese wet mixing techniques.

Equipment	Details	On land, Europe	On land, Japan
Mixing machine	Number of mixing rods	1–3	1–4
	Diameter of mixing tool	0,4 m to 0,9 m	1,0 m to 1,6 m
	Maximum depth of treatment	25 m	48 m
	Position of binder outlet	Rod	Rod and blade
	Injection pressure	500 kPa to 1 000 kPa	300 kPa to 600 kPa
Batching plant	Amount of slurry storage	3 m^3 to 6 m^3	3 m^3
	Supplying capacity	0,08 m^3/min to 0,25 m^3/min	0,25 m^3/min to 1 m^3/min
Binder storage tank	Maximum capacity		30 t

Table 3. Typical execution values of European and Japanese wet mixing techniques.

Mixing machine	On land, Europe	On land, Japan	Marine, Japan
Penetration speed of mixing shaft	0,5 m/min to 1,5 m/min	1,0 m/min.	1,0 m/min.
Retrieval speed of mixing shaft	3,0 m/min to 5,0 m/min	0,7 m/min to 1,0 m/min	1,0 m/min.
Rotation speed of mixing blades	25 rev/min to 50 rev/min	20 rev/min to 40 rev/min	20 rev/min to 60 rev/min
Blade rotation number	mostly continuous flight auger	350 per meter	350 per meter
Amount of binder injected	80 kg/m^3 to 450 kg/m^3	70 kg/m^3 to 300 kg/m^3	70 kg/m^3 to 300 kg/m^3
Injection phase	Penetration and/or retrieval	Penetration and/or retrieval	Penetration and/or retrieval

5.5 Design Aspects

In Europe, the general principles and concepts of geotechnical design, are covered by Eurocode 7 ENV 1997–1 1993, Part 1: *Geotechnical design, general rules; Part 2: Geotechnical design, ground investigation and testing*. Design aspects related to the execution of deep mixing work are covered by prEN 14679 "*Execution of special geotechnical works — Deep mixing*". This standard expands on design only where necessary, but provides full coverage of the construction and supervision requirements. These aspects refer to the installation method, the choice of binder, laboratory and field testing and their influence on the design of the column layout and performance. As deep mixing is a ground improvement process, design encompasses two distinct aspects:

- *"functional design"* describes the way in which the treated soil and the untreated soil interact to produce the required overall behaviour;
- *"process design"* describes the means by which the required performance characteristics are obtained from the treated soil by selecting and modifying the process control parameters.

The scope of the application of deep mixing is to handle and solve problems associated with the following aspects:

- settlement reduction (e.g. of embankments and structures);
- improvement of stability (structures and embankments);
- support of slopes and excavations;
- improvement of bearing capacity and reduction of settlement and lateral spreading due to dynamic and cyclic loading (e.g. in seismic regions);
- immobilisation and/or confinement of waste deposits or polluted soils;
- construction of containment structures;
- reduction of vibrations and their effects on structures and human beings.

5.6 Design Principles

Design considerations are discussed in detail in Annex B of prEN 14679. The ground treated with deep mixing must be designed and executed in such a manner that the supported structure, during its intended life and with appropriate degree of reliability and cost-effectiveness, will remain fit for the use for which it is intended and sustain all actions and influences that are likely to occur during execution and use. This requires that the serviceability and ultimate limit states are satisfied.

The requirements for the serviceability and ultimate limit states are to be specified by the client. The design shall be in accordance with the requirements put forward in ENV 1997-1, Eurocode 7: Geotechnical design, Part 1: General rules.

So-called iterative design, based on a follow-up of the results obtained by various testing methods, is an important part of the design. Here, the main focus is placed upon those factors that are important for the execution and the purpose of deep mixing. The design is made for the most unfavourable combinations of loads, which could occur during construction and service.

The deep mixing process may involve a short-term decreasing resistance to failure in consequence of induced excess pore water pressure and soil displacements. The mixed-in-place columns should be arranged in a way to avoid that possible planes of weakness in some columns installed could have a negative influence on the stability. In the stability analysis it is important to take into account the differences in stress vs. strain relationship between treated and untreated soil. For excavation support, the most important parameters are the compressive strength of the treated soil and arching. Figure 21 outlines the iterative process combining functional design and process design.

Stability

Often the purpose of soil treatment is to stabilise slopes, embankments or trench walls. In this case, the columns should preferably be installed in a number of walls on both sides, perpendicular to the slope, the embankment or the trench. The stability is analysed on the basis of the weighted mean strength properties of the untreated soil and those of the columns. Failure is normally assumed to take place along a plane, or curved, failure surface in which the shear strength of the columns and the shear strength of the surrounding soil are both mobilised.

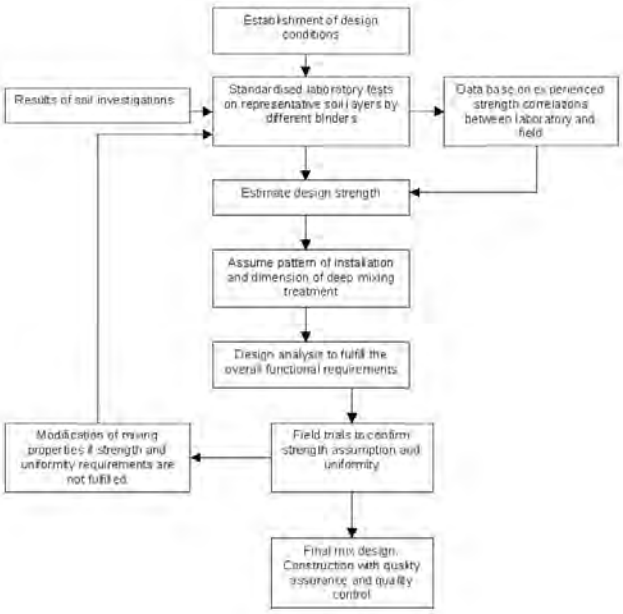


Fig. 21. Iterative design process, including laboratory testing, functional design, field trials and process design according to prEN 14679.

Influence of Column Location along the Potential Failure Surface

In the case of single columns being used for stability purpose the risk of bending failure of the columns must be considered. The columns will behave differently if situated in the active zone, or in the more or less pure shear zone, or in the passive zone of the potential failure surface. In the active zone the axial load on the column contributes to increasing the shearing or bending resistance while in the passive zone the columns may even rupture in tension. Therefore, columns in the active zone benefit most to improving the stability condition. In the shear and passive zones columns arranged as buttress walls or as a block are more effective in preventing shear failure than single columns.

Overlapping of Columns

Columns installed for the purpose of improving stability are commonly placed in single or double rows along, and perpendicular to, a slope, an excavation or an embankment. This increases the efficiency in comparison with single columns in that the negative effect of local column weakness is reduced as well as the risk of bending failure of the columns.

The moment resistance of the individual column rows should be sufficiently high not to be the cause of failure. Overlapping of the columns in the individual rows to create a column wall increases the moment resistance and overturning can be avoided by increasing the length of the rows and thus the number of columns in the rows. It is important that the shear strength of the treated soil in the overlapping zone is high enough and that the overlap of the columns is sufficient. It is important that the verticality of overlapping columns is maintained over the whole length. The shear strength of the stabilised soil in the overlapping zone usually governs the lateral resistance of the column rows.

Column Separation

Failure may occur in the shear zone due to separation of columns in the row when the slip surface is located close to the top of the columns and the tensile resistance is low within the overlapping zone. Such a separation reduces the shear resistance of the column wall. It is expected that the tensile resistance of the treated soil in the overlapping zone is about 5 % to 15 % of the unconfined compressive strength (it can be lower or higher depending upon the quality and efficiency of deep mixing).

Dowel Action of Column Rows

The dowel resistance of the columns will be decisive when the failure surface is located close to the bottom of a row. When the columns have separated from the adjacent columns the shear resistance per column in the row will be the same as the shear resistance of single columns.

Overturning of a Row of End-bearing Columns

The axial load on columns situated at the end of a row with end-bearing columns can be very high when the column row is subjected to a rotational movement. The maximum axial load thus obtained should be less than the load corresponding to the unconfined compression strength of the column.

Structural Wall Applications

Structural walls with reinforcement beams are commonly designed using the principle of arching.

Block Type Applications

As the properties of in-situ treated soil are quite different from those of untreated surrounding soil, it is assumed that the treated soil is a rigid structural member buried in the ground to transfer the external loads to a reliable stratum. For the sake of simplicity, the design concept is analogous to the design procedure for gravity type structures, such as concrete retaining structures.

The first step in the procedure includes stability analysis of the superstructure to ensure that the superstructure and the treated soil behave as a unit.

The second step includes stability analysis of the treated soil due to external action in which sliding failure, overturning failure and bearing capacity are evaluated.

The third step includes internal stability analysis in which the stresses induced in the treated soil by the external forces are analysed and confirmed to be less than the allowable values. Finally, the displacement of the treated soil is analysed.

In seismic design of the superstructure, the seismic intensity analysis is applied in Japan; the dynamic cyclic loads are converted to static load by multiplying the unit weight of the structure by the seismic coefficient.

In the case of more complex treatment patterns, relying on the interaction between the treated soil and the untreated soil between columns it is desirable to apply more sophisticated 2-D or 3-D elasto-plastic FEM analyses to examine stresses developed in the improved ground and displacement of the improved ground. Of course, the quality of the results is strongly influenced by the correct selection of input parameters.

Settlement

The design related to the deformation of mixed-in-place columns or elements or structures used for foundations or retaining walls shall be in accordance with ENV 1997-1, Eurocode 7: Geotechnical design - Part 1: General rules.

The treated columns, installed in order to reduce settlement of embankments, are mostly placed in some regular triangular or square pattern. Settlement analysis is generally based on the assumptions of equal strain conditions — in other words, arching is presumed to redistribute the load so that the vertical strains at a certain depth become equal in columns and surrounding soil.

For a group of columns the average settlement will be reduced by counteracting shear stresses in the untreated soil, mobilised along the perimeter of the group. Only a small relative displacement (a few mm) is required to mobilise the shear strength of the soil. The counteracting shear stresses will cause angular distortion in the improved soil along the perimeter of the group and, consequently, induce differential settlement inside the group. The counteraction — hence the differential settlement — will be reduced with time by induced consolidation settlement in the surrounding soil. It is therefore usually ignored in the settlement analysis.

Rate of Settlement

In dry mixing where the permeability of the columns may be higher than the permeability of the surrounding soil, the columns may accelerate the consolidation process in a way similar to vertical drains. However, the rate of settlement is not governed by the drainage effect alone. When stiff treated soil and untreated soft cohesive soil co exist, the dominant phenomenon is the stress redistribution in the system with time. At the instant of loading, the applied load is carried by excess pore water pressure. Owing to gradually increasing stiffness of the columns, a gradual transition of load from the soil to the columns causes a time-bound reduction of the load carried by the soil. In consequence, the excess pore water pressure in the soft soil diminishes rapidly, even without the radial water flow. This stress redistribution is one of the major reasons for the settlement reduction and increased rate of settlement. Therefore, even if the permeability of the columns is of the same order of magnitude as the surrounding soil, the consolidation process is accelerated by the presence of the columns. Thus, the load share between soil and columns increases the average coefficient of one-dimensional consolidation. The column permeability decreases with time and with increasing confining pressure.

In wet mixing the hydraulic conductivity of the treated columns is generally of the same order of magnitude as, or lower than, the hydraulic conductivity of the surrounding untreated soil. Therefore, the consolidation process is governed by vertical one-dimensional water flow only. However, by the stress re-distribution, the rate of settlement is much higher than that calculated by one-dimensional consolidation.

Confinement

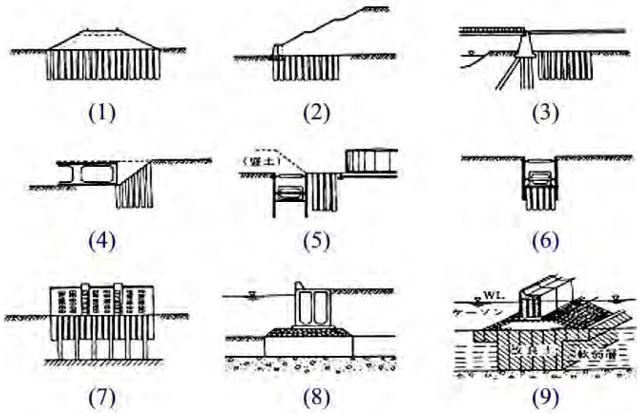
A confinement wall is formed by overlapping columns so that no leakage through the wall can take place. It is extremely important that the homogeneity of the columns is guaranteed and that leakage through the column wall is prevented. The thickness of the wall at the overlap and the permeability of overlap joints, have to be given sufficient tolerance in the design. Bentonite is commonly incorporated in wet mixing, in order to reduce the permeability of the treated soil.

If the objective of deep mixing is to create confinement of waste deposits or polluted soils, the durability of the treated soil becomes one of the most important design aspects. The reaction between the treated soil and the contaminant should be studied, especially when the waste has high acidity.

5.7 Areas of Application

Soil mixing is being used increasingly in Europe. However, the areas of application vary for different reasons, such as geotechnical conditions (soil type and soil strength), design considerations (stability, settlements, containment etc.), cost of competing foundation methods, availability of equipment and material, past experience and know-how etc.

Examples of the application of deep mixing for different purposes are illustrated in Fig. 22. Also given are the main design considerations for the respective application.



(1) Road Embankment: stability/settlement
(2) High embankment: stability
(3) Bridge Abutment: uneven settlement
(4) Cut Slope: stability
(5) Reducing the influence from nearby construction
(6) Braced Excavation: earth pressure/heave
(7) Pile foundation: lateral resistance
(8) Sea wall: bearing capacity
(9) Break-water: bearing capacity

Fig. 22. Application of deep mixing methods and geotechnical design requirements. After Terashi, (1997).

In Europe, several industrial, research, standardization and regulating organisations have an effect on the deep mixing industry. Ground improvement and in particular deep and shallow mixing methods can be used efficiently in order to improve the environmental conditions and safety in many European countries. However, their potential has not yet been realized by governmental authorities. In the following, a brief summary of their objectives and activities of authorities and regulating agencies is given.

5.8 European Committee for Standardisation

The mission of the European Committee on Standardization (CEN, www.cenorm.be) is to promote voluntary technical harmonization in Europe in conjunction with worldwide bodies and its European partners. Standards come from the voluntary work of participants representing all interests concerned: industry, authorities and civil society, contributing mainly through their national standards bodies. Draft standards are made public for consultation at large. The final, formal vote is binding for all members. The European Standards must be transposed into national standards and conflicting standards withdrawn. The Technical Committee on the Execution of Special Geotechnical Works (TC 288) of CEN prepares standards for different foundation methods. The standards are elaborated in cooperation with the European Federation of Foundation Contractors (EFFC) and address the execution procedures for geotechnical works (including testing and control methods) and the required material properties. Working Group 10 has been charged with the subject area of deep soil mixing, including wet and dry methods. The Technical Code for Deep Mixing (prEN 14679) has been prepared and accepted, following the national inquiries.

5.9 European Federation of Foundation Contractors

The European Federation of Foundation Contractors (EFFC, www.effc.org) represents about 450 foundation contractors in 17 European countries. Member companies are specialist contractors in the construction industry who undertake the construction of all types of foundations and other geotechnical processes (i.e. piling, diaphragm walling, grouting, ground anchors, ground improvement, dewatering, etc). EFFC's objectives are to promote the common interests of members of the federation; to improve standards of workmanship; and to maintain high standards of technical competence, safety and innovation throughout the European foundation sector.

EFFC's main activities are performed within Working Groups. The Technical Working Group prepares EU technical codes for specialist geotechnical and foundation in cooperation with the CEN Technical Committee TC288.

5.10 European Spatial Planning Observatory Network

Natural and technical hazards are of various types - earthquakes, flooding, drought, forest fires, volcanic eruptions and winter storms as well as risks relating to nuclear power plants, large dams and oil spills. In order to contain the impact of these hazards on people and property, the European Spatial Planning Observatory Network (ESPON, www.espon.lu) was established. Since 2002, ESPON performs studies and research covering the territory of 29 European countries, the 25 current EU member states, 2 candidate countries (Bulgaria and Romania) and 2 non-member states (Norway and Switzerland). The ESPON project focuses on the typologisation of risks and hazards as well as the risk profile of regions (hazard potential and vulnerability). Based on the experiences made with the vulnerability and risk maps, as well as in the case study areas, recommendations for spatial planning towards risk reduction are elaborated.

The results of the ESPON project will have a fundamental impact on the future development of Europe. Geo-related hazards affect many European countries and the associated risks have a significant effect on the development of the various regions. In the following, the following natural hazards will be briefly discussed: flooding, landslides and earthquakes.

5.11 Swedish Deep Stabilization Research Centre

The Swedish Deep Stabilization Research Centre (SD, www.swedgeo.se/Sd) was founded in 1995 with the aim to initiate and implement comprehensive R&D activities related to dry mixing methods and their practical applications. The objectives and activities were formulated as an industry-wide effort, including government and municipal authorities, material suppliers, contractors, consultants, the Swedish Geotechnical Institute (SGI) and universities. During the progress of the project, the scope was adapted to also include mass stabilization. The main objectives of SD were to:

• establish functional requirements for deep mixing regarding safety and maintenance,

• provide a platform for increased application areas of the method,

• create export opportunities for the industry, by introduction of system concepts for reinforced ground,

• introduce innovative application method aiming at increased competitiveness, overall economy and potential cost savings,

• reduce construction time and avoiding restrictions during the construction phase,

• assure a high competence level by contacts between project owners, contractors, material suppliers, consultants and researchers.

The activities of SD ended in 2001 and resulted in a large number of publications. SD produced 12 reports, several of them in English. These will be presented in more detail below.

5.12 Stabilisation/Solidification Treatment and Remediation Network

The UK government (EPSRC) funded Engineering Network on Stabilisation/Solidification Treatment and Remediation (StarNet), has been established and includes leading UK scientists and engineers, organisations and regulators involved with S/S technologies. The key scientific and technical issues for S/S technologies addressed by the Network comprise:

(a) binder selection,

(b) technology selection,

(c) testing and performance level,

(d) long-term performance and environmental impact,

(e) quality assurance and quality control issues and

(f) good practice guidance documents.

The project has organized workshops and recently the International Conference on Stabilisation /Solidification Treatment and Remediation.

5.13 Geo-Environmental Regulations

Geo-related problems are becoming increasingly important especially in urban areas and their surroundings. Urbanisation requires the performance of geotechnical work often in densely populated and congested areas. In northern Europe, urbanisation and infrastructure development are the main causes of soil degradation, whereas erosion is the most important factor in the Mediterranean region.

The use of land for infrastructure development can be considered as irreversible in a moderate time scale, since it makes soil unavailable for several generations. The amount of soil loss due to urbanization and infrastructure development is high in Belgium, Germany and the Netherlands and low, but increasing in Greece, Portugal and Spain. In the Mediterranean countries urbanisation is associated with the tourism industry. Cities in southern Europe are more vulnerable and at greater risk for geo-related problems compared to the cities in northern Europe. Many cities are situated along the coastline, rivers or on soft sediments where the ground normally consists of soft soil as clays or loose sand, such conditions are of importance. Reworking and removal of the soil surface can contribute to loss of biological diversity, harm to the ecosystem as well as land degradation and erosion. Several EU Directives have an impact on the geo-environmental situation and affect the foundation industry and in particular soil mixing applications. They regulate how soils, fill and waste material and water (surface and ground water) are handled. Environmental matters related to geotechnical works are handled by different authorities and also by the geotechnical community itself. The geotechnical community must take a leading role so that a constructive development can be assured.

European Environment Agency

The European Environment Agency (EAA) is the leading public body in Europe dedicated to providing sound, independent information on the environment to policy-makers and the public. An EU body, the Agency is open to all nations that share its objectives. It currently has 31 member countries. The EU Framework on Waste includes an obligation to promote self-sufficiency on a national level by waste minimisation, recycling and reclamation and the use of waste as an energy source. In northern Europe, urbanisation and infrastructure development are the main causes of soil degradation, whereas erosion is the most important factor in the Mediterranean region. The use of land for infrastructure development can be considered as irreversible in a moderate time scale, since it makes soil unavailable for several generations. The amount of soil loss due to urbanization and infrastructure development is high in Belgium, Germany and the Netherlands and low, but increasing in Greece, Portugal and Spain. In the Mediterranean countries urbanisation is associated with the tourism industry. Cities in southern Europe are more vulnerable and at greater risk for geo-related problems compared to the cities in northern Europe. Many cities are situated along the coastline, rivers or on soft sediments where the ground normally consists of soft soil as clays or loose sand, such conditions are of importance. Reworking and removal of the soil surface can contribute to loss of biological diversity, harm to the ecosystem as well as land degradation and erosion.

European Water Framework Directive

The European Water Framework Directive (WFD) highlights the need for a comprehensive approach for management of our surface- and groundwater resources to achieve the overall goal of “good status” in all waters. Future geotechnical works will in many respects be governed by the WFD. One of the objectives of the WFD is to provide a framework for integrated management of groundwater and surface water for the first time at European level. A general requirement "good ecological status" and "good chemical status" was introduced to cover all surface waters. The presumption is that groundwater should not be polluted at all. Measures should be taken to ensure the protection of groundwater from all contamination, according to the principle of minimum anthropogenic impact.

Landfill Directive

The objective of the Landfill Directive - Council Directive 99/31/EC - is to prevent or reduce as far as possible negative effects on the environment from the land filling of waste, by introducing stringent technical requirements for waste and landfills. The Directive is intended to prevent or reduce the adverse effects of the landfill of waste on the environment, in particular on surface water, groundwater, soil, air and human health. It defines the different categories of waste (municipal waste, hazardous waste, non-hazardous waste and inert waste) and applies to all landfills, defined as waste disposal sites for the deposit of waste onto or into land.

6 GEO-HAZARDS

Geo-hazards, which directly affect the deep mixing industry, are flooding, landslides and earthquakes. Within the ESPON project, geo-hazards have been studied in the EU countries. A brief summary of the preliminary findings are given below.

6.1 Flood hazards

Floods are defined as high-water stages where water overflows its natural or artificial banks onto normally dry land, such as a river inundating its floodplain. Floods occur at more or less regular intervals along rivers but also further away from them. Storm surge can have a devastating impact on coastal regions and the hazard is affected by several factors, such as the local coastal geometry and the rise in water caused by the wind. This is particularly the case in gulf-shaped, shallow marginal seas, the estuaries of rivers and elongated lakes. The area most exposed to storm surge is the North Sea coast and specific areas of the Baltic Sea, Fig. 23.

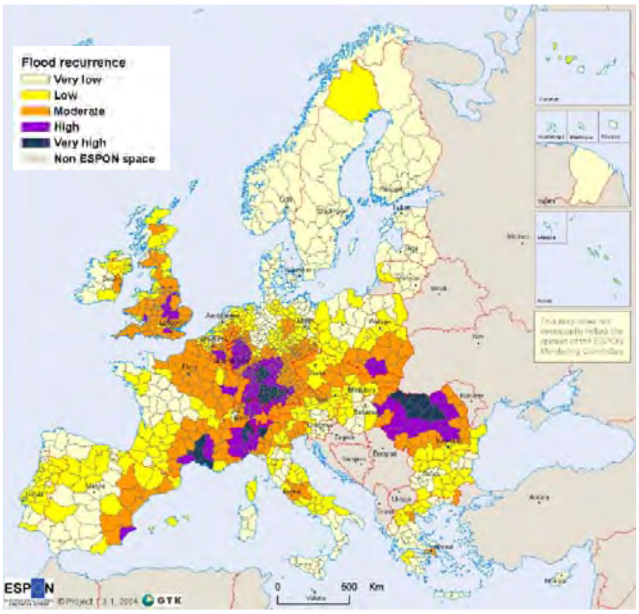


Fig. 23. Flood hazard recurrence in Europe, based on average number of large flood events during 1987 – 2002. ESPON (2004).

Wave action similar to a storm surge can also be caused by earthquakes occurring off-shore (tsunami), by volcanic action or by large land slides. Beside storm surges the two main types of flood are river flood and flash flood. The most important part of flood hazard identification is flood prone area delineation. Flood-prone areas are those subjected to inundation as a result of flooding at regular frequencies. The flood hazard intensity has been classified on the basis of average values using the time interval 1987 – 2002 (flash-floods excluded). The classification points out the frequency of large flooding events in Europe, meanwhile the magnitude of single flood events is not taken into consideration. The highest amount of large flood events during this period is concentrated in north-western Romania, South-Eastern France, Central and Southern Germany and in the east of England.

6.2 Landslides

In several regions in Europe, especially along rivers and in mountainous areas, the topography and the geological structure is of such a character that the risks of natural catastrophes, e.g. landslides and avalanches, are evident when certain conditions are fulfilled. Hydrological, hydrogeological, geological and geotechnical factors influence the probability of the occurrence of such catastrophes, as do the interference with the natural environment by human actions, such as tourism and land-use.

Landslides are the most widespread and undervalued natural hazard as even small slides can cause considerable economic loss. The term landslide includes a wide range of ground movements such as rock falls, deep failure of slopes, and shallow debris flows. Although gravity acting on a slope is the primary reason for a landslide, there are other contributing factors such as: erosion by rivers, ocean waves or glaciers, rock and soil slopes are weakened through saturation by snowmelt or heavy rains, earthquakes create stresses that make weak slopes fail or excess weight from fills, stockpiling of material or man-made structures.

The most important factors for landslides are hydrogeological, geological, geotechnical as well as vegetation. Different types of geology, morphology, climate, land use make it difficult to develop maps on an over-regional scale. Nevertheless, in order to obtain a major overview of the situation in Europe, an attempt is made by ESPON to develop a map based on slope steepness. Based on this information it was possible to give a first overview on the areas in Europe that experience landslides due to topographical reasons. However, such an assessment does not include areas with soft soils and low shear strength, where landslides can occur at moderate to low slope inclinations. Such areas are found in the vicinity of river shores and the coast line of lakes and the sea. Therefore, it is difficult to present large-scale maps regarding landslides, as these can be found only be detailed studies of the local geological and hydrogeological conditions. An assessment of landslide hazards requires in such areas local and regional experience. In order to coordinate European efforts regarding risk assessment associated with land slides and snow avalanches, a Concerted Action on Forecasting, Prevention and Reduction of Landslide and Avalanche Risks (CALAR) was implemented. The aim of the Concerted Action was to increase the knowledge of risk assessment as well as monitoring and warning systems for landslides and avalanches by dissemination of RTD results and technology transfer. The focus of the project was on forecasting, prevention and reduction of risks. The main results of CALAR were the compilation and dissemination of existing knowledge and methods of

Risk Assessment and Warning Systems related to landslide and avalanche problems. A further objective of CALAR was to create links between different scientific disciplines, end-users and administrators concerned with landslide and avalanche problems. A conference, *Living with Natural Hazards*, was held in 2000 in Vienna, where representatives of governmental organizations, researchers, insurance industry and administrators discussed future cooperation and coordination of mitigation methods. The outcome of the CALAR project was compiled in a Final Report.

In the Nordic countries, due to the particular geotechnical and hydro-geological conditions, with soft clay deposits of low shear strength and sensitivity to strength loss, land slides are a major problem. A report on landslide problems in the Nordic regions was included in the CALAR project (Massarsch, 1999).

6.3 Earthquakes

Of all natural phenomena, capable of inflicting disaster upon society, they are responsible for fewer deaths and smaller economic losses than for example storms and floods. However, since the degree of damage can be high over large areas, earthquakes have a large loss potential. The damage caused by earthquakes depends not only on the earthquake characteristics but also on the conditions of the affected area (structures and their foundations, slopes and excavations, embankments etc.).

In the ESPON study, peak ground accelerations from the Global Seismic Hazard Assessment Project (GSHAP) were used to produce an earthquake hazard map covering the whole of Europe, Fig 24.

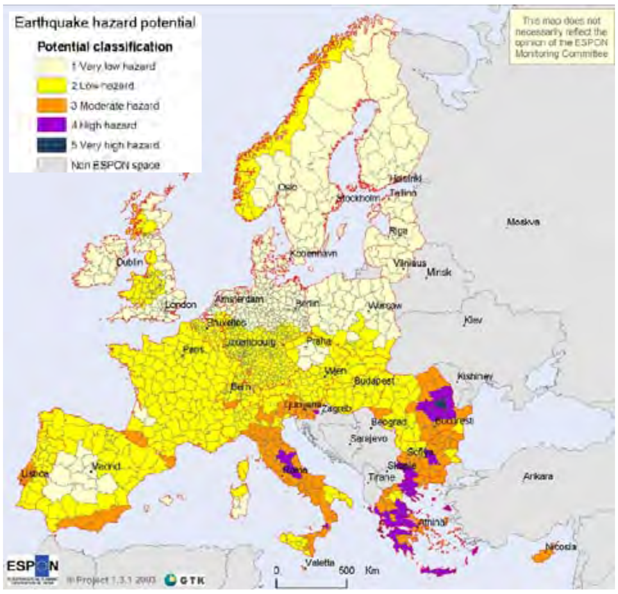


Fig. 24. Earthquake hazard in Europe, based on the average value of peak ground acceleration/acceleration of gravity (%). ESPON (2004).

The goal of the GSHAP project is to produce a homogeneous seismic hazard map for horizontal peak ground acceleration representative for stiff site conditions for the probability level of an occurrence or exceedance of 10% within 50 years. The peak acceleration is the maximum acceleration experienced by a particle during the course of the earthquake motion.

As can be concluded from Fig. 4, the earthquake hazard is concentrated in South-Eastern areas of Europe, e.g. Greece, Italy, Romania. Earthquake-prone regions such as Iceland and the Balkan countries are not included in the study.

7 CONFERENCES AND R&D ACTIVITIES

A number of regional and international conferences and workshops have taken place during the past decade. These were organized by professional or learned societies (e.g. ISSMGE), by national organizations (e.g. Deep Stabilization Institute, SD), or as part of European research or standardization activities (e.g. CEN/TC 288 Working Group 10).

7.1 European Geotechnical Conferences

Two European conferences on Soil Mechanics and Geotechnical Engineering were held in Amsterdam (1999) and Prague (2003). The main theme of the Amsterdam conference was “Geotechnical Engineering for transportation infrastructure”. Over 25 papers addressed deep mixing applications related to the construction of highways, railways, tunnelling and port construction projects. The theme of the Prague conference was “Geotechnical problems with man-made and man-influenced ground”. Surprisingly, only few papers were related to deep mixing and ground improvement problems.

Nordic Geotechnical Conferences

An International Conference on Dry Mixing Methods for Deep Soil Stabilization was held in Stockholm in 1999. The scope of the conference included the following themes: Application of dry mix methods for deep soil stabilization, Properties of binders and stabilized soils, Design methods and behaviour of stabilized soils, Case records, prediction and performance, Quality control of dry mix methods, Equipment for dry mix methods for deep soil stabilization.

Two Nordic Geotechnical Meetings were held in Helsinki (2000) and in Sweden (2004). Several papers addressed the application of mainly dry mixing methods in the Nordic countries.

An international conference on ground improvement (grouting, soil improvement and geosystems including reinforcement), 4th GIGS, was held in Helsinki in June 2000. The proceedings contain several interesting papers on deep and shallow soil mixing.

Other Conferences and Workshops

A workshop on deep mixing, organized by Working Group 10 of CEN/TC 288, was held in London in 2000 and followed by the Tokyo Workshop 2002 on Deep Mixing. The Tokyo Workshop was documented in proceedings, which describe the application of dry and wet mixing methods in Japan, Europe and North America.

In 2005, a UK-funded Engineering Network on Stabilisation/Solidification Treatment and Remediation, has held an International conference on stabilisation-solidification treatment and remediation. This conference addressed mainly environmental aspects of soil stabilisation, containment and encapsulation.

7.2 Research Efforts

EuroSoilStab Project

On the European level, the EuroSoilStab research project (1997-2001), which was carried out by 17 partners and which was funded by the EU, addressed "Development and design of construction methods to stabilize soft organic soils". The objective of the project was to develop and prove novel competitive design and construction techniques, backed by guidance documents, to stabilise soft organic soils for the construction of rail, road and other infrastructure, thereby enabling economic construction on land that was previously considered unsuitable. The project involved laboratory studies and field trials and aimed to cover the development of binders, laboratory testing of binders and soils, full-scale testing using both dry and wet mixing, measurement and back analysis of the full-scale behaviour and the completion of a design guide to EC7. The findings of the project, which included several field tests, are documented in the Final Report – Design Guide Soft Soil Stabilization, Holm (2003).

Swedish Deep Stabilization Research Centre

The most comprehensive R&D effort in the area of dry mixing in Europe during the past decade was initiated and financed by the Swedish Deep Stabilization Research Centre (SD). The activities of SD ended in 2001 and resulted in a large number of publications. SD produced 12 reports, several of them in English. The reports can be downloaded from the SD web site. Below follows a brief summary of the main reports.

Report 1 – "Compilation of experience of lime-cement columns", (Edstam, 1997). Experience from lime-cement column projects was compiled and analysed. The information comprises over five million metres of lime-cement columns installed throughout Sweden, mainly during the period 1985-1995. Extensive information was also acquired from test sites with well-documented measuring sections, including details of the properties of the natural clay, the properties of the columns, expected and observed behaviour.

Report 2 – "Preliminary investigations of the influence of the type of quicklime on stabilisation results", (Åhnberg & Pihl, 1997). The investigations were performed in the laboratory and comprised tests on eight types of lime in two different clays. The pilot study shows that the type of lime used can be of major importance for the stabilisation result even when the differences in properties such as degree of calcination, grain size, CaO content, etc. are relatively small.

Report 3 – "Stabilisation of organic soil with cement- and puzzolanic reactions – Preliminary study", (Axelsson et al, 2000; in Swedish). The report points out the possibility of stabilising mud and peat by determining the shear strength of samples stabilized in the laboratory. Samples of stabilized soil were produced in the laboratory and the strength of the samples was determined with unconfined compression tests. Different binders were used, consisting of cement (four different types), lime and residual material from industry.

Report 4 – "Test embankment on gyttja and sulphide clay reinforced with lime/cement columns in Norrala", (Larsson, 1999; in Swedish). In early 1996, an instrumented test embankment was built on very soft organic soil and sulphide clay reinforced with lime/cement columns. The test embankment was constructed in the Norrala Valley, at a location where a planned combined railway and road embankment was to cross the valley. This embankment constituted part of the "Hälsingekusten" project involving the construction of both a new highway and a new railway along part of the Gulf of Bothnia. Previous experience of deep stabilisation of organic soil and sulphide clay was very limited. The purpose of the test embankment was therefore to determine whether a sufficient reinforcement of these types of soil could be achieved to safely carry the relatively high embankment across the valley.

Report 5 – "Mass Stabilization", (Jelisic, 1999; in Swedish). The purpose of this licentiate thesis was to investigate suitable methods for the determination of strength and deformation properties of mass-stabilized soft soils. The report comprises also a study of performed projects in Sweden and Finland. A test embankment on mass-stabilized peat is presented and measured properties of the stabilised peat as well as settlements, pore pressure and temperature are presented and discussed.

Report 6 – "Mixing mechanisms and mixing processes used in lime/cement columns", (Larsson; 2000; in Swedish). The purpose of this licentiate thesis was to form a basis for development of the mixing process by increasing knowledge of fundamental theories and mechanisms when mixing binders and soft soils.

Report 7 – "Deformation behaviour of lime/cement column stabilized clay", (Baker, 2000). This study was aimed at developing a settlement design method that takes account of the effect of stiffness difference between the column and the surrounding soil on the rate of consolidation. The properties of lime/cement treated soil are presented based on laboratory and field tests. Three mathematical models are presented, two of which are numerical and one is an analytical elastic model. The analytical model is used to increase the understanding of long-term total settlement as well as the stresses caused by an applied load. In the first numerical, the finite element method has been applied using a three-dimensional model to study the stress distribution behaviour. The second numerical model is a finite difference model used to calculate the consolidation settlement of lime/cement column stabilized soil.

Report 8 – "Deep stabilization with lime cement columns. Methods for quality control in the field", (Axelsson, 2001; in Swedish). The main object of this licentiate thesis is to develop and test methods for checking the quality of the finished columns in situ, but also to give a summary of present methods in Sweden and in the rest of the world. Methods for checking the quality of lime cement columns have gradually been developed from ordinary geotechnical sounding methods to more specific methods. The main part of the thesis is focused on the experiences obtained from field- and laboratory studies. Some recommendations are given on performance of sounding tests and further development of the equipment.

Report 9 – "The function of different binding agents in deep stabilization", (Janz & Johansson, 2001). This report deals with deep mixing of soft soils. Chemical reactions occurring when using different binders as cement, quick lime, granulated blast furnace slag and fly ash are discussed. The function of binders in different soft soils, clay, silt, gyttja and peat is presented. In the report is also discussed the effect on the properties of the stabilised soil of the water content of the soil, the fineness of the binder and the prevailing temperature during curing.

Report 10 – "Mitigation of Track and Ground Vibrations by High Speed Train at Ledsgård, Sweden"; (Holm et al., 2002). Excessive vibrations were observed at a section (Ledsgård) of the West Coast Line between Gothenburg and Kungsbacka in Sweden when the traffic with high speed trains started. Banverket (the Swedish National Rail Administration) initiated a research and development project and comprehensive measurements and analyses were performed. The dry deep mixing method was chosen to reduce the vibrations. In this report the design, execution and measurements of vibrations before and after the deep mixing are presented.

Report 11 – "Environmental Effects for ground stabilization", (Rydberg & Andersson, 2003; in Swedish). In this report the life cycle analysis is used to investigate and declare methods and materials for deep soil mixing with lime-cement columns, mass stabilisation and surface stabilisation. The influence on the environment can be quantified and assessed when selecting technical solution.

Report 12 – "Mixing Processes for Ground Improvement by Deep Mixing", (Larsson, 2003). In this doctoral thesis the basic mechanisms in mixing binding agents into soil and the factors that influence the uniformity of the stabilised soil are studied. Advanced statistical methods have been used to analyse the results of two field tests regarding the influence of several factors. The concept of sufficient mixture quality is discussed.

8 STANDARDISATION WORK IN EUROPE

8.1 Standard on Deep Mixing

A Technical Code for Deep Mixing - prEN 14679 - *"Execution of special geotechnical works" was* prepared by CEN/TC 288 Working Group 10. The working group - comprising delegates from 9 European countries - commenced work in February 2000. Also experts from Japan took part in the meetings of the working group and contributed to the formulation of the final draft. The document has passed the CEN Enquiry and has been subject to formal voting. The document is intended to stand alongside Eurocode 7, ENV 1997–1 1993, Part 1: Geotechnical design, general rules; Part 2: Geotechnical design, ground investigation and testing.

The standard addresses execution aspect and expands on design only where necessary, but provides full coverage of the construction and supervision requirements. It establishes general principles for the execution, testing, supervision and monitoring of deep mixing works carried out by two different methods: dry mixing and wet mixing. Deep mixing considered in this Standard is limited to methods, which involve:

a) mixing by rotating mechanical mixing tools where the lateral support provided to the surrounding soil is not removed;

b) treatment of the soil to a minimum depth of 3 m;

c) different shapes and configurations, consisting of either single columns, panels, grids, blocks, walls or any combination of more than one single column, overlapping or not;

d) treatment of natural soil, fill, waste deposits and slurries, etc.;

e) other ground improvement methods using similar techniques exist.

Guidance on practical aspects of deep mixing, such as execution procedures and equipment, is given in Annex A of the standard. Methods of testing, specification and assessment of design parameters, which are affected by execution, are presented in Annex B. A brief description of the standard and its objectives is given in a paper to this conference (Hansbo & Massarsch, 2005).

8.2 Eurocode - Geotechnical Design

Eurocode EN 1997 shall be applied to the geotechnical aspects of the design of buildings and civil engineering works. It is concerned with the requirements for strength, stability, serviceability and durability of structures. It covers the following topics: Basis of geotechnical design; Geotechnical data; Supervision of construction, monitoring and maintenance; Fill, dewatering, ground improvement and reinforcement; Spread foundations; Pile foundations; Anchorages; Retaining structures.

9 EXAMPLES OF DEEP MIXING APPLICATIONS

In this section, typical applications of deep mixing in Europe are described. These comprise:

- Foundation support
- Retention systems
- Ground treatment
- Hydraulic cut-off walls
- Environmental remediation.

9.1 Foundation Support

In many applications, the purpose of dry deep mixing is the reduction of settlement and the increase of bearing capacity of weak foundation soil, as well as the prevention of sliding failure. On-land applications usually comprise road and railway embankments, buildings, industrial halls, tanks, bridge abutments, retaining walls and underground facilities. Waterfront applications can include quay walls and revetments.

The installation patterns typically employ single or combined columns with variable spacing for settlement reduction applications, while combined walls, lattices and blocks are used when dealing with high loads and/or horizontal forces. An increasing tendency to apply economical low values of the area improvement ratio can be observed in recent times, depending on the adopted deep mixing method and the achievable column strength. Design of such patterns requires rigorous analysis of the interaction between treated and untreated soil.

The strength of deep mixing elements may differ significantly within the range determined by low-capacity lime/cement columns, with a shear strength of about 0.15 MPa, and high-capacity structural elements having unconfined compressive strength in the order of 5 MPa, which perform similar to piles or caissons. The external loads are usually transferred down to the bearing layer resulting in a fixed type improvement, but can be also partly or wholly transferred to the foundation soil when a more interactive or even a floating type of improvement is desired. The choice of the required strength and of the load transfer system is dictated by the purpose of the deep mixing application, and reflects the mechanical capabilities and characteristics of the particular method used.

When deep soil mixing is applied to support shallow embankments or foundation slabs to reduce differential settlement, the individual column quality is less important, and the overall performance depends mainly on the soil to column interaction. Such a design concept of soil/structure interaction is applied by the Nordic Method and is often combined with preloading to accelerate settlement. This concept has proved to be efficient and cost-effective. On the other hand, when deep mixing is performed to support high embankments or heavily loaded foundations, and where horizontal loads or shear forces are significant, the quality of load-bearing columns is essential to prevent progressive failure mechanisms. The same applies for low values of the ratio of area improvement.

In bridge construction the deep mixing columns can be used to act as the pier foundation for the abutment, or to prevent lateral thrust and sliding by reducing the earth pressure behind the abutment. They can also reduce settlement of the bridge approach zone. In the case of buildings, deep mixing is an alternative solution to conventional deep foundation methods, particularly in seismic-prone areas. Since columns can be closely spaced, the foundation dimensions in plan remain relatively small, which contributes to the overall cost-effectiveness of this foundation solution.

9.2 Retention Systems

Retention systems comprise applications associated with restraining the earth pressure mobilised during deep excavations and vertical cuts in soft ground, with protection of structures surrounding excavations, measures against base heave, and prevention of landslides and slope failure. In these applications, wall- and grid-type column patterns are mainly used, while the soil-binder mix is typically designed to achieve high strength and stiffness. To overcome soil and water lateral pressures the columns should have adequate internal shear resistance. Other key requirements for successful construction are a high degree of column homogeneity and maintaining verticality tolerance to achieve the minimum required designed thickness of columns effectively in continuous contact. It is also important that early strength gain is sufficiently retarded to prevent problems when constructing secondary intercut columns.

Steel pipes or H-beams can be installed in columns executed with the wet mixing method to increase the bending resistance and create a structural wall for excavation support. Elongated mixing time and/or full restroking are usually applied to ensure easier installation of soldier elements immediately after mixing. Panels of mixed soil between H-beam reinforcement are designed to work in arching, as in a “Berliner Verbau”-type wall (e.g. Ausserlechner et al., 2003). Concrete facing, tieback anchors or stage struts are typically used in combination with walls constructed by deep mixing. Drainage media may be required behind the wall to prevent build-up of excess hydrostatic pressures. Deep circular shafts can be constructed using 2 to 3 concentric rings of overlapping deep mixing columns, acting together in hoop compression.

Columns can be installed within an excavation to resist base heave, where they act like dowels penetrating through potential sliding planes. In some cases the sides of the excavation are stabilised to increase the passive earth pressure and to reduce the penetration length of sheet piling or diaphragm walls.

Soil mixing is also applied to stabilise landslides and critical slopes. With suitable column arrangements, typically in the form of walls, grids, cells and blocks which intersect a potential failure surface, the combined shear strength of soil is improved and the factor of safety is increased.

There are also novel applications comprising of soil nailing and installation of special anchors using deep mixing. Special anchors can be also installed with the Nordic Method.

9.3 Ground Treatment

Ground treatment works usually involve substantial volumes of unobstructed soft soils and fills to be improved on-land, at waterfront areas and offshore with relatively high area improvement ratios. Typical examples are large developing projects including the construction of roads and tunnels on soft soils, stabilisation of reclaimed areas or river banks, and the strengthening of sea-bottom sediments. The purpose of improvement is mainly the reduction of settlement and an increase of bearing capacity, as well as prevention of sliding failure. Novel applications include the installation of wave-impeding deep mixing blocks of high rigidity beneath or near the foundation to reduce adverse effects caused by vibration on surrounding structures. Depending on the project requirements, deep and shallow soil mixing methods can be applied, including mass stabilisation.

Ground treatment works also comprise of dry and wet method soil stabilisation to a low strength, on the order of 0.2 to 0.5 MPa (unconfined compressive strength), using a reduced amount of cement and cheaper supplementary binders, like fly ash and gypsum. In case of the wet method the amount of slurry injected into the soil can be increased, hence improving the uniformity of mixing as compared to standard deep mixing applications using cement grout. High initial moisture content of the soil may have an adverse effect on the compressive strength and/or hardening process after treatment, as observed in soft Finnish clay in the Old City Bay area in Helsinki (Vähäaho, 2002). As a consequence, dry mixing may be the better option for very wet soils.

Underground blocks of low-strength deep mixing may be used to increase passive resistance and minimise heave at the bottom of excavation, allowing at the same time easy driving of sheet pilling elements or piles directly into or through the improved ground. Moderate strength deep mixing can also be used to improve soft soil to allow steady digging by the shield tunnel machine.

9.4 Hydraulic Cut-off Walls

Hydraulic cut-offs walls are constructed by deep mixing to intercept the seepage flow path. The columns/panels are typically installed through the permeable strata to some cut-off level, usually penetrating 0.5 to 1 m into a clay layer or finishing at the top of the bedrock. The soils treated are generally highly permeable coarse deposits, or interbedded strata of fine- and coarse-grained soils.

The applications mainly involve rehabilitation and/or upgrading of older water-retaining structures to meet new regulations for safe operation. Typical examples are earth-fill dams, dyke embankments and river banks. In the case of excavations, the supporting deep mixing walls may additionally serve to prevent seepage of groundwater towards the pit. When a conventional elevation of a river dyke crest is not possible, steel H-beams can be installed in deep mixing columns to support concrete superstructures or light dismountable protection walls on the crest to prevent overtopping (e.g. Topolnicki, 2003).

Since the hydraulic conductivity and continuity of the cut-off wall are of primary importance, careful design of slurry mixes tailored to soil conditions, and adequate control of overlapping zones and verticality are required, especially when cut-off walls are executed to a large depth with single shaft mixing equipment. For deep mixing walls the unconfined compressive strength is typically in the range of 0.7 to 3 MPa, and higher if steel reinforcement is installed, while the permeability is normally between 10^{-8} to 10^{-9} m/s. When bentonite and/or clayey stone dust and/or fly ash are added to the slurry mix the permeability can be reduced to 10^{-9} to 10^{-10} m/s, with associated decrease of the unconfined compressive strength usually below 1 MPa.

9.5 Environmental Remediation

Environmental applications emerged during the past 10 years and mainly involve installation of containment barriers and solidification/stabilisation of contaminated soils and sludges. In the United Kingdom wet deep mixing for ground improvement was employed in early 1990s for the construction of temporary shafts, of approximately 4 m internal diameter and up to 15 m deep. In this concept 2 to 3 concentric unreinforced overlapping rings were created by 75 cm diameter secant columns, which were designed to act together in hoop compression. The columns were installed with a simple auger-type mixing tool, using five passes of the tool over a 1 m withdrawal length. Around 1995 soil mixing was introduced for geo-environmental applications, with growing importance.

Fixation is much harder to achieve, as it requires contact of the chemical reagent with the contaminant. This is easier in sandy soils but very difficult in clayey soils. At an experimental level, soil mixing has also been used to introduce micro-organisms-based grout for bioremediation purposes, acid/base reagents for neutralisation, and oxidation reagents for chemical reaction.

Soil mixing containment systems include passive and active type barriers constructed around a part, or the entire periphery of the contaminated site. Passive barriers resemble hydraulic cut-off walls described above and are installed to prevent migration of polluted leachates out of the contaminated site. Active barriers have permeability comparable to the native soil. They are typically constructed as ‘gates’ in passive barriers to reduce significant effects of the containment on the existing groundwater regime. With appropriate soil-mixed materials, such as modified alumina silicates, and adsorbance capacities, gates act as microchemical sieves, removing contaminants from groundwater as it passes through and allowing, in principle, only clean water to emerge on the other side. Four recent case histories covering this concept have been reported by Al-Tabbaa and Evans (2002). The deep mixing containment barriers are suitable for existing waste disposal deposits and new landfill facilities. However, grout composition and binder reactions with the contaminants in the short and long term perspective are key factors in the success of such applications.

Solidification/stabilisation of contaminated soils and sludges containing metals, semi-volatile organic compounds and low-level radioactive materials using wet- and dry method soil mixing started to be recognised as a favoured remediation option because of the advantages over other containment and remediation methods. These include reduced health and safety risks, elimination of off-site disposal, low cost, and speed of implementation.

By selecting appropriate equipment and procedures, the reagents can be uniformly injected at depth, and efficiently and reliably mixed with the soil or sludge present. In the case of soil contaminated with volatile compounds, negative pressure is kept under a hood placed over the mixing tool to pull any vapours or dust into the vapour treatment system.

10 RESEARCH AND FUTURE DEVELOPMENT NEEDS

Compared to other foundation methods, soil mixing is still in a development phase and well-documented case histories of novel applications and practical experience are needed. For many deep mixing applications, conventional design methods are not applicable, as the execution method affects the performance of the stabilized ground. It is also difficult to apply experience obtained from applications in one geological region, to projects in other areas without careful evaluation of the design assumptions and limitations of the method. Therefore research and technical development are needed in order to make design more economical and reliable. In the following the need for future research will be briefly discussed:

10.1 Materials and Binders

Binders are an important component of the deep mixing process. The total cost of deep mixing projects is affected by the type and amount of required stabilizing agent. The optimal binder selection and mixing ratio depend on the geotechnical properties of the material to be improved, but also on the geotechnical design of a project. This aspect is of particular importance for dry soil mixing, where in many cases the mixing ratio is relatively low.

Further research is required with respect to the application of dry and wet mixing in unusual materials, such as organic clays and peats.

An increasingly important area is the application of soil mixing for the solution of geo-environmental problems. Additional research is needed with respect to the appropriate choice of binder mixtures for different types of contaminated ground.

There is a need for standardized laboratory mixing procedures for optimal design of binder quantities. There is still a lack of understanding how the mixing energy applied during laboratory tests, can be correlated to in-situ conditions. At present, it is difficult to predict the increase of strength and stiffness of the improved ground during and after mixing. Therefore, in many cases, large-scale field tests are required to verify the design assumptions for important projects.

10.2 Analysis and Design Methods

The strength and deformation properties of individual columns and of the composite material (ground reinforced by columns or wall elements) are important for design. However, there is a lack of suitable testing methods, which provide information on the strength and deformation properties in situ.

In the case of the Nordic dry mixing method, the design assumes that the stabilized columns are flexible and interact with the surrounding soil. Additional studies are needed in order to verify the deformation properties of improved ground. Full-scale installations can provide valuable information on the stress strain behaviour of lime column reinforced embankments and slopes.

There is still uncertainty regarding the permeability – and drainage capacity - of columns created by different dry mixing binders.

The deformation properties of stabilized soil when subjected to dynamic and cyclic loading are not fully understood and further studies are needed.

The effect of the mixing process on the strength of the soil – and the possible temporary reduction of strength due to soil disturbance – is not fully understood.

Wet mixing methods can achieve rigid, pile- and wall-like elements, which can be installed into stiff bottom layers, while dry mixed columns usually are terminated above rigid strata. Stiff, rigid columns interact in a different way with the soil than the more flexible columns obtained by dry mixing. It is important that design engineers are aware of these differences.

10.3 Execution

At present, dry deep mixing is used mainly in the Nordic countries, with soft, often sensitive clays or silts and high water content. Experience is needed from dry mixing projects in stiff clays and silty or sandy soils.

In the case of dry mixing, the binder is introduced in the soil by air pressure. Additional research is needed to establish whether the injection of air affects the behaviour of the improved ground.

New “hybrid methods” are being introduced, where deep mixing is combined with jet grouting or trenching methods. Only limited experience is available from projects where these new methods have been used. Well-documented case histories can provide additional information, which can result in more efficient project design and execution.

10.4 Supervision, Testing and Monitoring

Field monitoring and the active control of the installation and mixing process are important for the reliable execution of deep mixing projects. At present, it is difficult to predict and verify the geometry of stabilized columns. Even with careful field monitoring equipment it is at present difficult to predict the actual column diameter (or its variation) in soils with variable layers.

Another subject for further studies is the control of the verticality of columns (accuracy of installation), especially in the case of overlapping columns with lengths exceeding 10 m. This aspect is of special importance when deep mixing is used to support slopes, high embankments and excavations.

The determination of the strength and deformation properties of stabilized columns is difficult by conventional geotechnical methods. There is a need for new, innovative testing and control methods. Seismic methods have the potential of providing valuable information about the stiffness of individual columns and of the column-reinforced soil. Other geophysical methods, such as the geo-radar could be used for geotechnical and geo-environmental applications.

10.5 Environmental Considerations

Binders can cause environmental problems, for instance when field personnel is exposed to unslaked lime and cement. European regulations can restrict the use of some binder types, which are potentially hazardous for the ground water.

Shallow and deep mixing methods have a large potential for the solidification or encapsulation of contaminated soils. However, further research and additional field studies are needed for general application of deep mixing in this area.

11 MARKET SHARES, TRENDS AND FUTURE EXPECTATIONS

In the Nordic countries (Finland, Norway and Sweden), dry deep mixing is primarily used for reduction of settlements and for improvement of stability, especially for road and railway embankments on soft soil deposits. An important advantage compared to ground improvement by e.g. vertical drains is the rapid gain in soil strength, resulting in shorter construction time.

Deep mixing is also employed to a lesser extent for the foundation of smaller buildings and bridges, as well as for stabilization of excavations and natural slopes. When properly designed and executed, considerable cost reductions can be achieved compared to pile foundations. Experience has been favourable from a technical perspective, as well as from an economic viewpoint. Application of Wet Deep Mixing

In Central Europe, the wet deep mixing method dominates and is used for a variety of projects, such as retaining structures, foundation elements for buildings and bridges, the construction of cut-off walls etc.

There is a growing market for the wet mixing method for the remediation of contaminated soils. Extensive research and development work is presently under way especially in the United Kingdom.

12 CONCLUSIONS

The geological and geotechnical situation in Europe is complex. There is a potentially large market for deep mixing methods, for instance related to the increasing urbanization and expansion of the transportation infrastructure.

Different deep and shallow mixing methods have been developed in different parts of Europe. The optimal mixing method for a specific project depends on a variety of factors, such as the geological and geotechnical conditions, the structural requirements, the experience of the design engineer and the availability of suitable equipment and qualified personnel.

The introduction and implementation of the European Standard on Deep Mixing prEN 14679 is an important step towards the increased acceptance and wider application of deep mixing in Europe.

In the recent past, several new mixing methods and applications have been introduced. However, practical experience is still limited to certain soil conditions and specific applications.

Design engineers are often not aware of the potential but also of the limitations of deep mixing and rely to a large extent on the competence and practical experience of the contractor. Thus, monitoring and control of the execution of deep mixing projects is important in order to assure cost-effective and reliable applications.

There is a large potential for new applications of deep mixing, in particular in the environmental field.

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