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GROUND IMPROVEMENT TECHNOLOGIES DEEP SOIL MIXING METHODS. FUNDAMENTAL ASPECTS

BY

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Abstract. This paper presents the main theoretical aspects of deep soil mixing technologies. These methods are defined as the processes by which soil is mixed *in-situ* with stabilizing agents, using special execution equipment. As a result of the interaction of the two components, is obtained a composite soil with superior mechanical characteristics compared to natural ground, thus eliminating the issues of low strength and stiffness, high compressibility, susceptibility to liquefaction, etc. In the paper are presented withal the following: a brief history of the development of deep mixing methods, classification methods, the advantages of their use and the factors that influence technologies performance. The article also details the most commonly used binders and the way how react with certain types of soil.

Key words: deep soil mixing; binders; composite soil; soil stabilization.

1. Introduction

Strength, stability and durability of a construction is based on rational design and execution that takes into account the interdependence manifested between three components: superstructure, foundation and ground foundation and the need to work together of this assembly.

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As a consequence of industry development, achievement of a large number of new constructions and expansion of those existing, wordwide appears the need to use weak foundation soils which from geotechnical engineering point of view are characterized by: low bearing capacity, high deformability and aggressiveness to materials constituting the buildings foundations.

The method or degree of improvement depends on nature and properties of foundation soil, structural solution and importance of construction type, intensity and mode of loads transmission to the ground.

The purpose of this papers is to treat various topics concerning deep soil mixing technologies regarded as alternatives to traditional methods of improving poor quality of natural soil. The article defines soil stabilization concept by deep mixing, presents a brief history of development of this technology, highlights factors that directly influence quality of composite ground resulted and advantages of using this method

2. Definition of the Deep Mixing Technologies

Along with other methods to improve soil in depth such as: compaction with columns of soil, ballast, sand, crushed stone and other local materials, static or dynamic consolidation etc., deep mixing methods aimed to stabilizing in-situ soil, by mixing it with various stabilizing agents (lime, cement, fly ash, chemical or biological reagents) as a suspension or powder (Porbaha, 1988). As a consequence of reactions between ground and binders, physical and chemical soil properties are changing which lead to rigid or semi-rigid inclusions characterized by variable geometry, engineering and environmental properties substantially improved.

The inclusions resulted by deep mixing represent a cost-effective solution for situations where physical and mechanical properties of soil from a particular site does not allow the application of shallow foundation and deep foundation would involve an oversize compared to what is needed (ASIRI National Project).

In order to apply deep mixing technologies are used various execution equipment, provided with special mixing tools like: cutting blades, wheels, rods with folding arms, rotating shafts, blades and augers through which the ground is disaggregated and mixed with stabilizing agents, without requiring to excavate it.

Deep mixing as soil stabilization method leads to enhanced engineering characteristics reflected by increased strenght, low compressibility, permeability and erodability, liquefaction mitigation, reduction of water content and increased durability in dynamic or cyclic actions (Nicholson & Peter, 2014).

Another important goal of this method is solidification and stabilization of contaminated soils (Porbaha, 1988).

3. Brief History of Development of Deep Mixing Methods

The first research and development of deep mixing technology were made in 1954 in the United States, since 1960s in Japan and later in Sweden has applied this method using lime as binder, for treatment of soft soils and clays. In 1975 it was used cement as fluid cement grout to stabilize soft marine soils, creating a new notion: “Cement Deep Mixing”. In 1987 in France, the Bachy Company developed “Colmix” which provides mixing and compacting the cemented soil during withdrawal of the mixing tools and this was a significant development for Europe (Bruce, 2000).

Currently, the deep mixing technology has become the most popular ground improvement method and it is used worldwide (*e.g.* Japan, Malaysia, France, Belgium, Singapore, Thailand, Vietnam) under various names and acronyms such as: CDM (cement deep mixing), DSM (deep soil mixing), SMW (soil mix wall), DLM (deep lime mixing), SWING (spreadable wing method), DJM (dry jet mixing), JACSMAN (jet and churning system management) etc. (Bruce & DiMillio, 2000).

4. Classification Criterias of Deep Mixing Methods

The specialized literature (Porbaha, 1988; Bruce *et al.*, 2001) emphasizes three criterias that make the difference between the multitude of methods that are based on the principle of in situ admixture soil, which are:

4.1. The Geometry of Treated Ground

This classification criterion is strictly dependent of: ground conditions, the size of loads transmitted by the superstructure and bearing capacity required. Thus, in this respect, are distinguished the following types of geometries, Fig.1 (Porbaha, 1988) – *block-type improvement*, *wall-type improvement*, *lattice or grid type improvement* and *column-type improvement*.

It is clear that block type and wall type are the most stable configurations due to the higher volume of treated soil, but on the other hand, are expensive because of the necessary materials and workmanship. Considering the economic aspect, the column types are the most commonly used in practice which are carried out without requiring overlappings.

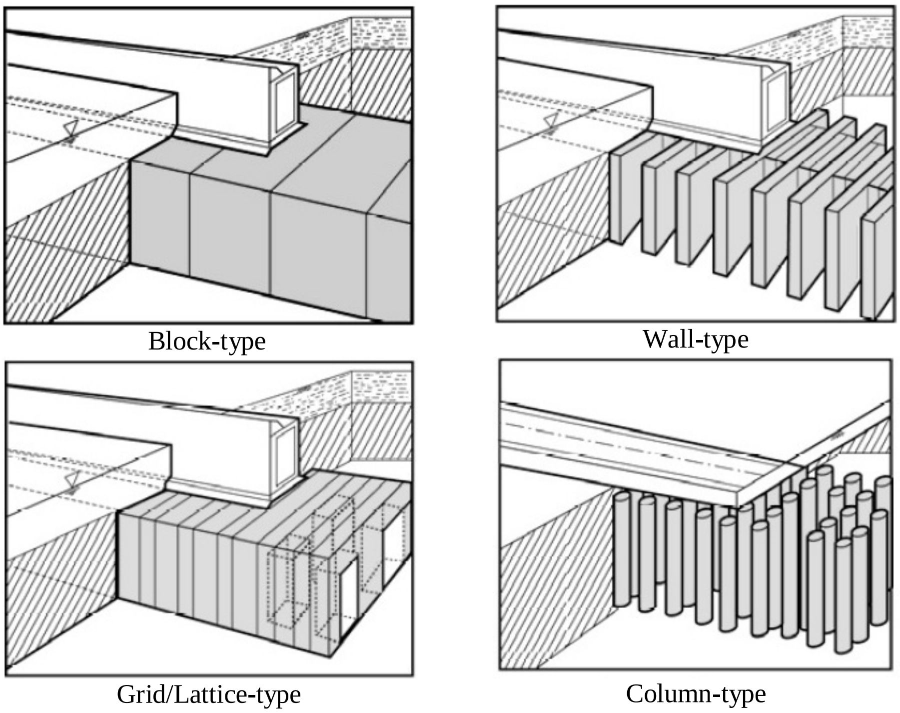

Fig. 1 – Specific geometries of treated soil mass.

4.2. Aggregation State of the Binder

According to this criterion, admixture soil can be done with binders either in *powder* form, either in *slurry* or *grout* form, which entails the following classification of deep mixing methods: *wet method* and *dry method* (Bruce *et al*., 2001). Wet method can be used successfully for soft clays, sludges, fine-grained sands and gravel with a low water content while the dry method can be applied when ground conditions is characterized by soft soils and high water content.

4.3. Procedure of Mixing Soil with Stabilization Agent

The execution technology involves in situ soil mixing with different kind of binders, aspect which can be performed through the following procedures:

a) disaggregation and mechanical mixing using rotative tools;

b) disaggregation and mixing using pressure jet;

c) disaggregation and mixing using both high pressure but also rotative blades.

5. Benefits of Using Deep Mixing Methods

The application of deep mixing techniques for treating and improving soils with poor mechanical properties presents a series of advantages, which are listed below (Porbaha, 1988; Nicholson & Peter, 2014):

1º Reducing resources consumption which entails minimizing total cost.

2º Rapid solutions that allow to consolidate an existing structure without interrupting its use for a long time.

3º Not require evacuation of treated soil.

4º In terms of environmental impact, are not polluting, generating low noises and vibrations.

5º The diversity of execution equipment provide high productivity.

6º Real-time control on the quality of executed elements by modern monitoring systems.

7º The wide range of applications, solving a large part of geotechnical issues regarding: supporting deep excavations and protection of surrounding buildings, reinforcement of roads and railways subgrade, slope stabilization – retaining walls, cut-off walls and seepage control, ground improvement under an existing construction or in order to apply shallow foundations for a future construction, remediation for polluted soils.

6. Factors which Influence Soil Stabilization by Deep Mixing Technologies

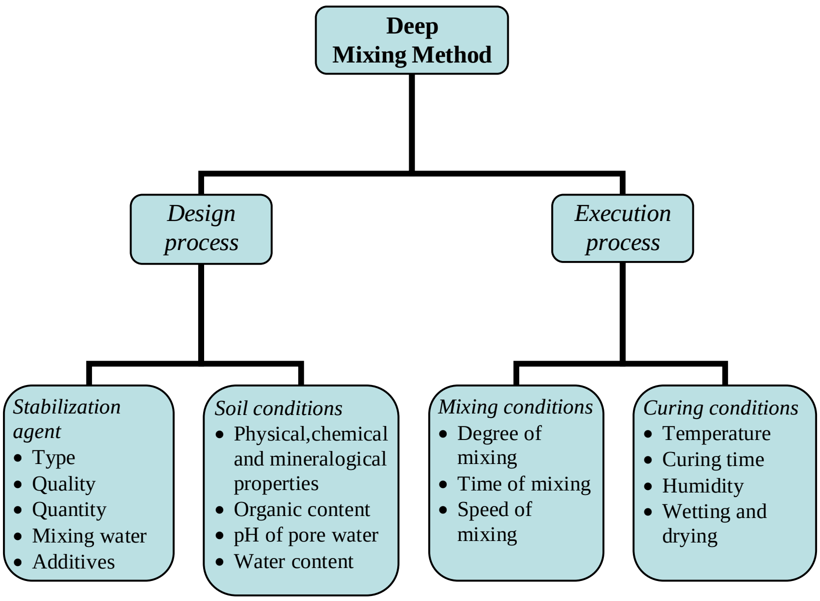

Fig. 2 – Factors which affect the performance of Deep Mixing Technology (Terashi, 1997).

6.1. Binder Types

a) *Lime*

Lime (the non-hydraulic binder) is the first binder used to improve the geotechnical characteristics of the ground. In present, lime soil treatment, in order to increase the shear strength, reduction of the deformations and decrease water content, it is widely used in various applications such as roads, highways, embankments, dams, airfields, etc. (Tran, 2014).

Lime can be used in two forms: *quicklime* (lumps or powder) and *hydrated lime* (slurry or powder). Quicklime or burnt lime is calcium oxide CaO which is obtained by burning limestone or calcium carbonate $CaCO_3$ at high temperature, process called calcination. By mixing a wet soil with quicklime, the moisture of the soil is reduced, as a result of two processes (Nicholson, 2014): hydration process of the lime and evaporation process due to heat as a result of the exothermic hydration of the quicklime.

Hydrated lime or slaked lime is calcium hydroxide $Ca(OH)_2$ and is obtained by treating quicklime with water.

Chemical and mineralogical composition of soils is an essential factor in the stabilization with any type of binder.

Reactive soils like, clays, are composed predominantly of aluminum hydro-silicates. Clay particles possess a negative electrical charge on their surfaces. Neutralization of negative charge is accomplished by adsorption of cations. After mixing lime with clayey soils, hydration reactions of the lime are performed. Further, between clay particles and hydrated lime arise two types of processes (Bulletin 326, 2004):

a) *cation exchange* by which calcium cations Ca^{++}, from hydrated lime, are migrating to clay particles and replacing the lower charge cations and water molecules; as a result clay particles lose their adsorption ability of water molecules and their strength is increased;

b) *puzzolanic reactions or cementation* whereby silica and alumina react with calcium and water, giving rise to strong cementitious products like calcium silicate hydrates (CSH), calcium aluminate hydrates (CAS), calcium alumino-silicate hydrates (CASH) (similar to those formed by mixing with cement); these reactions can proceed days, months and sometimes years.

Lime can be used also for less reactive soils, characterized by a low plasticity and clay content less that 7%. To stabilize these types of soils, fly ash or blast furnace slag can be added to bring an intake of silica and alumina, needed in pozzolanic reactions (Bulletin 326, 2004).

b) *Cement*

Silicate cement (Portland cement) is the most frequently used binder in deep mixing technologies, providing higher strengths by comparison to lime. Portland cement is a hydraulic binder which is obtained by fine grinding of cement clinker, which in turn, it is a result of firing at high temperature a clay and limestone mixture. The chemical composition of Portland cement type consists in: silica, alumina, calcium aluminoferrite and various oxides (Rujanu, 2009).

Currently, cement is used to stabilize all types of soils. The cement dose ranging between 6%,…,15% by dry weight of soil, depending on its type. The best results are obtained in case of gravels and sands with small amounts of clay and silt. For the ground with a high degree of moisture and high organic content, using cement as a hardening agent is not the most economical solution (Nicholson, 2014). The researches in the field have emphasized that a clayey soil, which has a fine grain, requiring a higher quantity of cement to increase strength and stiffness of native soil, compared to coarse grained soils (Farouk & Shahien, 2013).

Similar to lime, when cement comes in contact with water, the exothermic hydration of cement occurs. Further, when hydration products meet clay particles, the pozzolanic reactions are occurring and as a result, cementitious compounds are formed (CSH, CAH, CASH). These resulting cementitious products are responsible for superior characteristics and enhanced strengths of the cement soil (Ouhadi *et al*., 2014).

c) *Fly Ash*

Fly ash is a solid waste, “a by-product of coal combustion”, which is produced worldwide, in tremendous amounts (about 750 million tons per year) (Shaheen *et al*., 2014). Fly ash is used in deep mixing technologies, by itself or in combination with other binders such as cement, lime etc., and is considered one of the cheapest stabilizing agents.

Production conditions and type of the coal from which they come from, directly influences the mineralogical, chemical and physical properties of fly ashes. The chemical composition of fly ash includes the following: silica, alumina and iron oxides. Soil blending with fly ash influences the soil hydraulic conductivity and by reducting the permeability, water holding capacity is enhanced. Soil pH can be also modified, depending on the chemical nature of the fly ash (Shaheen *et al*., 2014).

7. Conclusions

This article details the basic concepts necessary to understand how deep mixing methods lead to improving difficult soil conditions. Diversity of deep soil mixing technologies, wide field of application and the multitude of advantages, have entailed the popularity and intense use of these methods worldwide. The paper highlights the essential features of the most common binders, following to develop in future articles design aspects, execution technologies and applications.

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TEHNOLOGII DE IMBUNĂTĂȚIRE A PĂMÂNTULUI
Metode de malaxare în adâncime. Aspecte fundamentale

(Rezumat)

Se prezintă principalele aspecte privind tehnologiile de stabilizare a pământului în adâncime prin amestecare. Aceste metode sunt definite ca fiind procedeele prin care pământul este amestecat *in-situ* cu agenți de stabilizare, utilizând echipamente de execuție speciale. În urma reacțiilor dintre cele două componente rezultă un material compozit cu caracteristici superioare terenului natural, eliminând astfel problemele privind rezistența şi rigiditatea scăzută, compresibilitatea mare, susceptibilitatea la lichefiere, etc. În lucrare mai sunt prezentate următoarele: un scurt istoric de dezvoltare a metodelor de amestecare în adâncime, clasificări ale acestor metode, avantajele utilizării acestora precum şi factorii care influențează performanțele tehnologiilor. De asemenea, articolul evidențiază cei mai utilizați lianți, precum şi mecanismele de interacțiune cu anumite tipuri de pământuri.