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Technical session 2a: Ground improvement

Séances techniques 2a: Amélioration des sols

T. Edil
University of Wisconsin-Madison, USA
M. Kitazume
Port and Airport Research Institute, Yokosuka, Japan
Y. Watabe
Port and Airport Research Institute, Yokosuka, Japan

1 INTRODUCTION

The total of 37 papers are submitted to Technical Session 2a on Ground Improvement, in which wide variety of improvement techniques except reinforcement technique and stone column technique are presented. The submitted papers can be classified as summarized in Table 1 according to the principle of improvement. All the submitted papers were invited to the oral presentation, which was held separately following this technical session. In the session, Prof. Tuncer Edil, the chairman of the session, briefly presented an opening address and overviewed ground improvement techniques. Dr. Masaki Kitazume, the general reporter, briefly presented the classification, principle and the history of development of ground improvement techniques, which was followed by presentation of outline of all the submitted papers in this session in order to point out the main topics of discussion. Then seven panelists were invited to present their discussion topics as summarized in Table 2. The floor discussions were followed and were chaired by the session chairman.

Table 1. Classification of submitted paper in the session.

Principle of improvement	Engineering method	no. of papers
Replacement	Excavation replacement	0
	Compulsory replacement	0
Drainage	Preloading	0
	Preloading with vertical drain	4
	Dewatering	0
	Chemical dewatering	0
Densification	Compaction by displacement and vibration	4
	Vibration compaction	1
	Impact compaction	2
Admixture stabilization	Mechanical mixing	15
	Jet mixing	1
	Grouting	7

Table 2. Panelists and discussion topics.

Panelist name	discussion topics
Dr. Abir Al-Tabbaa	Durability of cement-based grouts and binders
Dr. N. Jelisic	Experiences of the performed mass stabilization projects"
Prof. P.S.Pinto	Use of slurries for the construction of a plastic and flexible diaphragm wall
Mr. H. Rathmayer	Risk related to inhomogeneity of DM lime-cement stabilised soil & columns
Dr. J. Maertens	Quality control of ground improvement works
Prof. N.C. Consoli	On the micro-reinforcement of soils
Prof. Y.K. Chow	Ground improvement by dynamic compaction

In this article, discussion topics of seven panelists are briefly introduced together with some floor discussions.

2 DISCUSSION TOPICS

Dr. A. Al-Tabbaa (UK)

She presented the durability and environmental impact of cement treated soil. Durability and environmental acceptability are currently two major challenges facing the selection and performance of grouts and ground improvement binders. Increasingly, those materials are being used in aggressive ground conditions including contaminated land. Durability and increasing the life of those materials is essential in order to reduce future maintenance and repair costs. In her presentation, she focused on cement-based grouts and binders used in various geotechnical applications and addressed aspects of performance including the durability of cement-based grouts in aggressive environments, e.g. aggressive chemical and freeze-thaw cycles, and the development of new binders with improved durability and environmental acceptability. Outline of her presentation is introduced as follows:

A number of changes have taken place which affect cement-based grouts and binder: (i) they are being used in an increasing variety of contexts, both geotechnical and geoenvironmental; (ii) they are increasingly being used in more aggressive environments e.g. contaminated land; (iii) there is an increased incorporation of industrial by-products, which are continually changing in composition because of cleaner production processes; (iv) there is a need to increase the lifespan of materials because of the drives towards sustainability and (v) there is continued developments of more environmentally acceptable and sustainable cements to reduce the environmental impacts from the production of Portland cement.

One of the main durability problems of Portland cement is the leaching of calcium: firstly the portlandite (which is highly soluble and highly reactive) is dissolved and then the calcium silicate hydrate (C-S-H) is decalcified leading to its degradation. Durability problems include sulfate, chloride and acid attack, freeze-thaw and wet-dry cycling and long-term deterioration.

Her on-going research is investigating two areas of improving the durability of cement-based grouts and binders. The first is the incorporation of durability improving additives. The example used here is zeolite. The second is the investigation of a more durable cement and the example used here is magnesium oxide cement.

Like clay, zeolites are aluminosilicates. However they have a rigid three-dimensional structure which contains channels and cavities. They have large reaction surfaces and high cation exchange capacity. Zeolites are already widely used in a range of industrial and commercial processes including wastewater treatment, refinery distillation and in commercial detergents. In China they are widely used as a cement blending material.

Some of the advantages of zeolite in cement-based binders are listed here. Firstly, the highly porous structure of zeolite provides large reaction surfaces for the interaction with Portlandite hence consuming it. Secondly, zeolite in a cement matrix produces a hydration phase which contains less Portlanite and less Ca-rich C-S-H reducing leachability. Thirdly, zeolite produces a finer pore matrix in cement paste, reducing the permeability. Zeolite offers much improved durability compared to commonly used additives, which have durability improving properties, such as pulverised fuel ash and blastfurnace slag.

Related experimental work was carried out in which cement-based mixes, not containing zeolite, were immersed in sulphate and acid solutions for up to four days and showed extensive physical deterioration. Similar samples which contained zeolite, survived those two environments for over 200 days without any signs of physical damage.

Magnesium oxide (MgO) cements are a recent invention. Their main ingredient is magnesium oxide, or magnesia, which has to be reactive. This is produced by the calcining of magnesite (calcium carbonate) at a temperature of around 850^{o}C, this being much lower than the temperature used to produce Portland cement. The cement formulations also include a pozzolan, e.g. pulverised fuel ash, and Portland cement. One range of these cements is called Tec-cement which is a modified Portland cement in which a small quantity of reactive magnesia is added to Portland cement. Another range is Eco-cement which mainly consists of a pozzolan and reactive magnesia to which a small quantity of Portland cement is added.

The reason for the good durability performance of MgO cements is the fact that they hydrate to form Brucite (magnesium hydroxide) which is far less soluble and far less reactive than Portlandite. It therefore has much reduced leachability and much reduced reactions with anions. Brucite is also fibrous and has a layerd structure and hence it is additional able to trap sulphate and chloride ions within its structure. In addition, Brucite has a lower water demand leading to a denser paste, lower permeability and reduced freeze-thaw problems.

One technique being employed in the study of this cement is nano-indentation. Nano-indentation involves the formation of a cone-shaped indent on the surface of a material with the application of a force. From the load-displacement profile a number of physical and mechanical properties of the tested material can be obtained. The application of this technique to the study of the microstructure of Portland cement was pioneered by colleagues at MIT.

At the 10^{-6} m scale, a sample of Portland cement will consist of the two types of C-S-H, high density C-S-H and low density C-S-H. By applying nano-indentation to such a sample, one can map a profile of Young's modulus within the sample. This shows that the low density C-S-H forms around 67-70% of the sample and has an average E value of around 22 MPa. The high density C-S-H forms the remaining 30-33% of the sample and has a higher E value at an average of 30 MPa. If the same procedure is applied to a sample which is calcium leached, this shows that the E values of the low density and high density C-S-H types drastically reduced to 3 and 12 MPa respectively. This gives a clear indication of the effect of the calcium leaching on the stiffness of the C-S-H. Such observations are being linked to observations of stiffness and other properties carried out at the macro-scale using material blocks.

In summary of the presentation, she pointed out the discussion points as follows:

- There has been many changes affecting cement-based grouts and binders – but what is the impact on their durability?
- There are additives which offer vast durability benefits such as zeolite but would cost implications be a hindrance to their use?
- MgO cements are likely to be more durable than Portland cement. However as a new material, it will require extensive testing and validation. Also how long will be take the construction industry to accept alternative cements to Portland cement?
- Are there sufficient research efforts being carried out on the durability of cement-based grouts and binders? and
- Where should current and future research efforts be concentrated?

Dr. N. Jelisic (Sweden)

He presented some succesful case histories of mass stabilization technique. The technique has been developed in Nordic countries for improving the stability of road and railroad embankment by mixing organic clay at shallow depth with a binder, usually quicklime. The outline of his presentation is as follows:

The geotechnical properties of peat (low compressibility moduli and low bearing capacity) make it unsuitable as a base for road and railway embankments and, therefore, it has to be excavated and replaced with crushed rock or its geotechnical properties have to be improved by using the stabilization. Deep stabilization has been used in Scandinavia since the end of the 1970's. In the process of deep stabilization, strengthened columns are formed through the mixing of stabilizers preferably lime-cement (50:50). The mixing tools that have been used for deep stabilization are inefficient for the homogenization of the fibre of peat and because of that a new mixing technique (new mixing tools) has been developed. This mixing technique is called mass stabilization (although the term block stabilization is also used).

Mass stabilization is carried out with a mixing tool installed on an excavator. Mixing in both the horizontal and vertical directions is carried out so that a block (monolith) of strengthened peat, which spreads the load from the embankment to deeper soil layers, is formed through the effect of the stabilizer. The thickness of the block varies between 1 and 5 m according to the height of the embankment. The block must have certain shear and tensile strengths, elasticity moduli and homogeneity to fulfil its purpose.

The equipment for mass stabilization consists of a mass stabilization machine, a stabilizer tank (20 m^3), scales, compressor and mixing tool, which is installed on the modified excavation machine arm. The stabilizer is fed pneumatically and the amount of the stabilizer is measured through weighing. The diameter of the mixing tool is normally 600 – 800 mm and the rotation speed lies between 80 and 100 r. p. m.

Mass stabilization has been used in over 30 different projects in Scandinavia since the beginning of the 1990's.

The main applications of mass stabilization technique have been to increase stability and reduce settlements in road and railway embankments constructed on peat. Mass stabilization has also been used for: foundations for oil and gas pipelines, foundations for water pipelines and sewers, foundations for buildings, stabilization of excavated soils, stabilization of dredged soils, stabilization of hazardous (chemical) wastes, stabilization of excavations for building foundations and soil improvement for ground adjacent to buildings.

A number of different stabilizers have been used for the different mass stabilization projects: Lohjamix V16, Lohjamix V17, cement, Merit 5000 with cement etc. The quantity of stabilizer used was generally between 150 and 200 kg/m^3. The Lohjamix stabilizers are made from different activators (cement, lime and aggregates) and from industrial by-products (such as fly ash, the end products of a sulphur removal process and blast-furnace slag) while the Merit 5000 stabilizer is made from granulated blast-furnace slag.

In most of the mass stabilization projects carried out the design shear strength (28 days) was fulfilled. It must be taken into consideration that the follow up investigations were almost always performed only at one occasion and in these cases just one or two weeks after the completion of mass stabilization work. This means that the investigations took place at the beginning of the curing process and although much higher shear strengths developed later on, the design shear strength (30 days) was achieved.

The settlements in the mass stabilization projects were, on average, between 0.5 and 1.0 m. It should be noted that the peat was moved twice; first, when it was prepared for stabilization and again when the stabilizer was added. Air subsequently penetrated the peat, which made it swell. Such swelling caused the natural ground to rise between 0.2 and 0.5 m. If this rise is deducted from the total settlement measured during the studied projects, it can be seen that the total settlement of stabilized peat was between 0.3 and 0.5 m. Furthermore, it can be seen that approximately 90% of the total settlement of stabilized peat develops during the first 24 hours.

Prof. P.S.Pinto (Portugal)

He presented some case histories, laboratory testing and execution technique of the diaphragm wall with self-hardening material for controlling the seepage flow in the earthdam. The outline of his presentation is as follows:

To control the seepage trough the foundation of an embankment dam with 50m high and 3000m long, a diaphragm wall with 20m depth was built in the main valley. The site investigations for the design and execution of the plastic and flexible diaphragm wall with a self hardening slurry are presented. The laboratory studies performed to characterise the constituents of the slurry, namely water, cement, bentonite and admixture, in order to optimise the slurry, related the permeability and deformability characteristics are described. The phases of execution, the supervision of execution and monitoring of the diaphragm wall are referred. The tests performed during the construction of the diaphragm wall, in order to respect the design specifications related the properties of density, viscosity, sand content, setting time, bleeding, compressive strength and permeability of the slurries are presented. The tests performed to assess the efficiency of the diaphragm wall are described.

Mr. H. Rathmayer (Finland)

He introduced laboratory testing, construction and strength property of treated soils with a mixture of cement and quicklime. In his presentation, the difference between the laboratory and field treated soils in the uniformity, density and magnitude of induced air content were presented. The outline of his presentation is as follows:

Several aspects related to the quality of DM lime-cement stabilisation are highlighted. The preparation of laboratory samples for binder optimisation differs essentially from the mixing procedure in the field (e.g. homogeneity, air content, density, temperature conditions). For obtaining good lab/in-situ relationship real simulation of the in-situ mixing procedure for the design of optimum binder quality and quantity is necessary, e.g with a small size pilot machinery. The strength properties of stabilised soil is a strongly dependent on w/c (water-cement ratio), thus high cement con-tent results in brittle behaviour which should be reflected in the safety philosophy applied in the design. Scandinavian post glacial clay deposits vary strongly in water content; to achieve uniform w/c ratio asks for real-time adjustment of binder quantity. Pressurized air applied as transport media is entrapped in the soil-binder mixture and reduces strength; pressure is usually increased for greater depth. Binder consumption is measured 30 – 40 m behind the mixing tool causing a time shift in QC measurement. Corrections for missing binder quantity may miss the target. Increased energy input during mixing produces better homogeneity at higher cost; the benefits are better predictable strength properties and thus reduced risk for the designer and client. The present high risk level could be reduced by linking on-site determined soil properties to the execution of the DM procedure together with a real-time QC by using sensors placed close to the mixing tool.

Compressive strength of stabilized soil at 28 day was found to depend on water cement ratio (w), fines content (μ) and humus content (h). Taking into account the strong variations of water content with depth in clay deposits the control of binder feeding is a mayor QA task and should preferably be located close to the mixing tool.

Several types of mixing tools are applied for DM column stabilization. Their energy input may vary to a great extent, depending on shape, inclination and number of blades and wings. If the design is based on laboratory samples mixed with dry binder in an open pot according to a non-standardized procedure the determined strength properties may differ essentially from those obtained at samples taken in-situ. Better mixing needs more time and this means higher costs of work performance.

The high differences in strength properties between laboratory design values and measured in-situ values were asked after. It is therefore of highest priority to built up correlations between standardized laboratory mixing procedures and the work execution depending on mixing tool and mixing intensity (number of blades, of rotations, inclination of wings, lifting speed etc.).

Shear strength determined in laboratory and shear strength determination in the field with penetration testing differ significantly from each other. Penetration tests in hard columns will need extremely high loads and are thus impractical. Penetration methods of which the resistance is measured at the top of the rod are misleading. Friction along rods must be taken into account. Penetration methods of which the resistance forces are measured at the tip of the rods are mostly recommended. To estimate the attainable strength one must reduce the strength obtained from laboratory tests with a factor of 0.3 – 0.6.

Dr. J. Maertens (Belgium)

He introduced some of the EURO Code, CEN/TC288, on Execution of special geotechnical works, grouting, jet grouting, deep mixing and dynamic compaction at first and then presented some attempts on quality control of improved ground. As the quality control, he emphasized that the flow rate and permeability of the drain are key issued for quality control in the vertical drain method, and the outlet pressure for the jet grouting method and the amount of sand introduced in the ground for the stone column method. Outline of his presentation is as follows;

Actually the level of quality control is not very high for ground improvement works. So it happens regularly that when the results doesn't correspond to the expectations, it is not possible to determine what has been going wrong.

In the first part of the presentation an overview will be given of the quality control methods described in the European Standards for the execution of special geotechnical works dealing with ground improvement (= grouting, jet-grouting, deep mixing, deep compaction …). In the second part some examples will be given of additional measurements that can be performed to improve the quality control, e.g.:

- for vertical drains:
  - flow capacity of the drains;
  - flow rate through the drains;
- for jet-grouting:
  - pressure in the grout just above the monitor;
  - flow rate of the spoil;
- for stone columns:
  - quantity of gravel in function of depth.

Prof. N.C. Consoli (Brazil)

He presented the mechanical property of reinforced treated soil, especially the effect of the initial stiffness and strain on the property. He presented some laboratory test results in triaxial tests and cylindrical shear tests. He concluded that the initial stiffness of the reinforce treated soil is not influenced so much by the fiber reinforcement but the ultimate strength increases by the reinforcement. The outline of his presentation is as follows:

Earlier studies of fiber soil-reinforcement have thus far been restricted to small to intermediate shear strains of approximately 0.1 – 20%, due to the restrictions of the standard equipment used (e.g. triaxial and direct shear tests). The objective of the present research was to study the behavior of fiber-reinforced soils ranging from very small shear strains to very large displacements, to determine what effect reinforcement would have on the initial stiffness, and also whether the improved strength would eventually deteriorate. High pressure isotropic compression tests, which included bender element stiffness measurements, and ring shear tests were carried out, as well as standard triaxial tests, in order to investigate the effect of fiber microreinforcement of different soils over a wide range of strains and displacements. Sandy, silty-sandy and clayey soils were used as matrixes, in which were inserted from zero to 0.5% (by weight) of polypropylene fibers that were 6 to 24 mm in length and 0.023 mm thick. The results show changes in the isotropic compression behavior due to the random inclusion of fibers into the soil. Two distinct and parallel normal compression lines were observed for the fiber-reinforced and non-reinforced soils. The fibers were exhumed after testing and it was found that fibers had both extended and broken, indicating that the fibers tend to suffer large plastic tensile deformations before breaking and that the fibers act under tension even in isotropic compression. At very small strains, the introduction of polypropylene fibers did not influence the initial stiffness of the materials studied. Ring shear results have also shown a marked influence of fiber-reinforcement on the ultimate strength, with no loss in shear strength, even at very large horizontal displacements.

Some questions were come from the floor, which included the applicability of his investigation on fiber-reinforcement to cohesive soils. As the answer, he pointed out that he already have results of ring shear tests on a fiber reinforced bentonite at high water content (about 100%). Is it possible to say that fiber reinforcement works even for such materials, improving both peak and post peak behavior, even though the improvement is not in the same proportions of the one obtained for the granular soil, and in the case of clays, once that the particles end with some orientation for the clayey soils, at very high shear strains, obtainable in ring shear tests, a reduction of the strength occurs, reaching similar values of the non-reinforced bentonite.

Prof. Y.K. Chow (Singapore)

He introduced an attempt on evaluating the improvement effect of dynamic compaction method by introducing the wave propagation theory. He also presented the high applicability of his evaluation model by comparing his calculations to the field measurements on the penetration depth and the improvement effect. The outline of his presentation is as follows:

Dynamic compaction is a simple and effective technique for the densification of granular soils in the field. In practice, the depth of improvement is generally estimated using the empirical equation $d = \alpha \sqrt{(WH)}$. This equation, however, does not take into account the characteristics of the soil nor does it give the engineer an appreciation of the effect of operational parameters such as the pounder weight, drop height, print spacing, number of drops per pass and number of passes. Extensive field trials for the selection of operational parameters are always necessary to minimize costs. Hence, there is little understanding of the inherent physical processes with the use of the above empirical equation. The need for the formulation of reliable predictive models that will give a better understanding of the mechanics of the dynamic compaction process cannot be overemphasized.

The presentation gives an overview of the development of predictive models for the analysis of dynamic compaction of granular soils. The development of a one-dimensional wave equation model which simulates the dynamic interaction between the pounder and the soil as well as the complex soil behaviour resulting from the propagation of the stress waves during impact will be discussed. The model accounts for the punch through phenomenon of the soil, nonlinear soil behaviour during impact and geometric damping in the soil. Case studies are presented to demonstrate the predictive ability of the model, viz the pounder penetration, degree and depth of improvement which compare favourably with field results. A method is also presented to facilitate the choice of print spacing on the level of ground improvement at the site and is verified by case studies. Together, a complete solution to the dynamic compaction problem is thus possible enabling a proper analysis and assessment of the effect of the different operational parameters that will help to minimize the number of costly and time-consuming field trials.

Recent two-dimensional (axisymmetric) finite element analyses with large strain dynamic formulation with a cap model for the soil demonstrate that in the initial blows the stress wave propagation induces transient K_0 compression due to lateral inertia resulting in a plane wave front which explains the success of the one-dimensional wave equation model in simulating this problem. In later blows, the effect transits to one of triaxial compression by which time a "saturation" state would have been reached and this sets a limit on the degree of improvement.

While the more complex two-dimensional (axisymmetric) finite element model which involves dynamic large strain formulation with a complicated soil model is more complete in terms of simulating the dynamic compaction process, the one-dimensional model captures many of the essential features of the problem and is a more practical tool. The different models have their role in providing a means for the analysis of the dynamic compaction problem and in providing a better understanding of the physical processes involved.

3 SUMMARY

After the presentations by seven panelists, some discussions were held with the panelists and the floor. The discussions covered various aspects of ground improvement techniques. For the deep mixing method, the effect of permeability and stiffness of treated soil column on the consolidation process of improved ground, quality control and assurance techniques, the strength difference of field strength and laboratory strength in jet type deep mixing method.

Although so wide variety of ground improvement techniques should be covered in this session 2a, very heated floor discussion was encouraged by the session chairman.

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