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Opportunity management as a chance – Ground Improvement solutions for heavily loaded structures

Les possibilités ouvertes par la gestion des opportunités – Solutions d'amélioration de sols pour des structures lourdement chargées

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ABSTRACT: Well-designed ground improvement options without compromising on stringent design criteria may effectively replace conventional foundation solutions for a wide range of applications involving heavy loads and structures sensitive to settlement. Opportunity management gives the chance to achieve the project scopes. Beneficial returns in terms of lowering construction costs and shortening construction time with consistency in quality are discussed in relation to the required capabilities and experiences of an organization to deliver the alternatives. Significant challenging geotechnical trends for the future are summarized as innovative alternative solutions require a more precise management and design of alternative opportunities.

RÉSUMÉ: Des options d'amélioration de sol, conçues sans compromis selon des critères rigoureux, peuvent effectivement se substituer aux solutions conventionnelles de fondation dans un vaste domaine impliquant des charges élevées et des structures sensibles aux tassements. La prise en compte de ces opportunités donne la possibilité d'atteindre les objectifs du projet. Les effets bénéfiques en termes de diminution des coûts de construction et de réduction des délais à qualité constante vont être examinés en fonction des exigences de qualification et d'expérience permettant de mettre en œuvre ces alternatives. Les grandes tendances géotechniques, complexes et prometteuses pour le futur sont résumées. Elles constituent des solutions innovantes exigeant une gestion et une conception rigoureuses de ces alternatives.

Keywords: Ground Improvement;Deep vibro compaction;Deep Soil Mixing;Opportunity management;

1 INTRODUCTION

More and more civil structures are commissioned as economies around the world grow and the requirements for improved infrastructure accelerate. This inevitably leads to scarcity of land and demands to construct over soft ground, be it formed naturally or artificially. Nowadays, the subject of soft ground engineering attracts a lot of interest and it involves state-of-art engineering practices. Deep foundation using piling techniques is a frequently adopted foundation solution in such circumstances. However, it may not be the only solution and often it is associated with relatively high cost as compared to other alternatives. In some occasions, deep foundation could even be an ineffective solution to adopt in soft ground. For a given scenario, there exists an optimal foundation solution that is technically sound, fit for its purpose and most economical. With rigorous design analysis and careful project execution, ground improvement also in combination with piles would be an efficient and more cost effective alternative to piled foundation only.

2 GEOTECHNICAL OPPORTUNITY MANAGEMENT

In the context of holistic opportunity management, the project scope has to be achieved taking into account cost, time and quality (Ahmed, 2001). In general it is also necessary to weigh the advantages and disadvantages to exploit opportunities in the optimization process and enable the evaluation of potential conflicting tendencies in individual areas (quality optimization requiring costs and time increase versus cost optimization in conjunction with lower quality, etc.). This process is naturally highly dependent on the ability of the organisation involed to recognize opportunities and the willingness to exploit them. Last but not least the expertise and experience available in the organization play a decisive role to achieve optimal solutions considering the engineering and operational capabilities of the organisation (human factor) (Figure 1).

These four influencing factors define a complex system of mutual dependencies in terms of technical as well as economic aspects and can offer substantial potential for optimization, esspecially during the initial phase of the project. These opportunities can only be exploited when there is adequate geotechnical competence involved in the initial phase of the project (interdisciplinary planning). The best opportunities for obtaining an optimal project design are encountered when determining the site characteristics as detailed as possible in particular.

The contract shall be designed accordingly, so that all participants have a common interest in exploiting these opportunities and share the risks incurred by exploiting them.

FIG.1. Factors influencing geotechnical opportunity management

To manage the site specific opportunities and risks optimally, the mutual interaction and influence of

- site specific characteristics,
- manufacturing technology and process,
- plant and equipment used for construction,
- personnel (competence and experience)

are of critical importance. To design an geotechnical opportunity in the interests of all partners involved in addition to the issues mentioned above, the geotechnical factors such as:

- (changes in the) soil characteristics at the site,
- technical product limitations and design methodologies,
- restrictions in the layout of the plant and equipment, as well as
- environmental factors

having an influence and should be addressed, defining the starting point for the optimization process. Therefor before an optimal geotechnical opportunity can be designed, it is essential to determine the detailed site characteristics first (Gudehus, 2002). The optimization process requires the study of alternative geotechnical solutions and their requirements on the soil mechanical parameters early on while planning the site investigation, which means that even in this phase, geotechnical expertise can open a range of opportunities. Furthermore, opportunity management is naturally controlled by the requirement of the construction task. During the process the opportunities as well as the risk inventories of individual alternatives also need to be examined and evaluated. The most economically acceptable alternative does not necessarily have to be the one with the lowest risk inventory, and the lowest probability of occurrence may not be associated with the alternative with the lowest influence on cost, schedule and quality.

To perform opportunity management in an organized manner in this complex system of geotechnical alternatives, expertise and competence in the following areas should be integrated into the project as early as possible:

- a wide range of geotechnical technologies
- the limits of application of the individual methods (technology, devices, etc.)
- the risk inventory of each method in connection with the ground conditions
- efficiency (cost) of the various methods and applications

3 BEST PRACTICE AND EVALUATION CRITERIA`S FOR OPTIMAL SOLUTIONS

If ground is to be subjected to additional loads which exceed its previous load levels, the geotechnical design requirements have to be established to determine suitability of designated technologies. Various codes and standards define the limit state conditions influenced by the ground:

- ultimate limit state design (position, design of load bearing members, total load bearing capacity of ground)
- serviceability limit state design (deformation, displacement),
- durability requirements of the products, materials used to construct

which have to be taken into consideration in the geotechnical design. If it is found, in the course of the geotechnical design, that the above limit state conditions are likely to occur, the following measures can be taken:

- unsuitable ground can be bypassed
- unsuitable ground can be replaced
- unsuitable ground can be made suitable.

When selecting the appropriate measures, in addition to taking into account the durability requirements, it is necessary, to determine the soil improvement requirements from the ultimate and serviceability state design in accordance with the geotechnical design categories. The general assessment criteria´s for any ground improvement technology or method are:

- predictability of the technology as a reliable method
- repeatability of the process
- design-ability of the method in combination with the subsoil conditions
- process as a controllable procedure (documented, monitored)

to evaluate the achievements of the improvement technology as well as the limitations (Raju V.R., Sondermann W.,2005).

4 GROUND IMPROVEMENT PROCEDURES

As a general rule, the desired results of ground improvement are as follows:

- increase in density and shear strength, having a positive effect on all stability problems
- reduction of compressibility, which has a positive effect on deformability
- influencing permeability for the purpose of
  - reducing water inflow/water outflow
  - increasing deformation speed
- improving homogeneity.

Many ground improvement techniques have been developed to treat soil particles to achieve best geotechnical properties. These techniques can be divided into the following categories (Sondermann W., Kirsch F. 2018):

Remove & replace*:* it is perhaps the oldest and simplest technique. This method involves removing and / or replacing weak soil with better material which has suitable properties for the use. It is generally applied to relatively shallow depth (usually up to 2 m). With more stringent environment protection regulations imposed by authorities, it has become more costly to dispose the weak soil in many countries, especially when the soil is contaminated with hazardous material.

Compaction / densification: this method improves soil properties by rearranging soil particles to denser state using mechanical means. Although surface compaction can be applied to many types of soils, deep compaction can only be effectively and economically used in cohesion-less soils.

Drainage / consolidation*:* soft soils are generally associated with high water content. Soil strength can be improved by forcing out the water. However, the process often takes a very long time in thick layer of cohesive soil due to low permeability and long drainage paths. To accelerate the process, drainage paths can be introduced. It is almost always used with surcharge, which preloads the soil to a higher degree of consolidation so it can carry intended loadings with little or no further consolidation.

Reinforcement*:* stiff elements can be introduced into weak soils to carry loads or redistribute loads so less loads are carried by the weak soils. Elements such as geotextile can also introduce tensile capacity into soil mass. Understanding the interactions and load transfer mechanism between stiffer elements and soil mass is vital in design.

Modification*:* soil properties can be completely changed by introduction of binding agents such as cement or lime. The modified soil would behave similar to very stiff to hard soils or even like low strength rock or concrete, depending on the soil and the amount of binding agent added.

Others*:* other ground improvement techniques such as ground freezing utilizes frozen water as binding agent to hold soil particles together, while electrical methods like electro-osmotic technique use electrical current to stabilize soil. These methods are less commonly used as compared to the other techniques.

The selection of the most suitable ground improvement method accompanied by the appropriate process sequences for any specific application must always be based on a thorough technical study and economic comparisons and references to the application limitations of the different methods.

5 COMBINATION OF GEOTECHNICAL TECHNOLOGIES

In standard design practice, a distinct gap exists between piling and ground improvement (GI) solutions used for foundation support. Piling is typically adopted for heavily loaded structures, such as high-rise buildings, bridges, large commercial centers, silos and other industrial objects, for which stringent bearing capacity, stability and settlement criteria must be satisfied. Conversely, GI solutions are usually considered to be of no or limited use for heavily loaded structures, mainly due to the perceived inability to limit total and differential settlements to an acceptable level. It should be noted, however, there is also a range of applications where piling and GI solutions may actually overlap. This is illustrated in Fig. 2, which shows tentative ranges of GI and piling solutions in a schematic load vs. settlement graph.

The combined figure reveals an overlapping area where piling and GI solutions may both be applicable for a given range of loads without compromising functional design criteria.

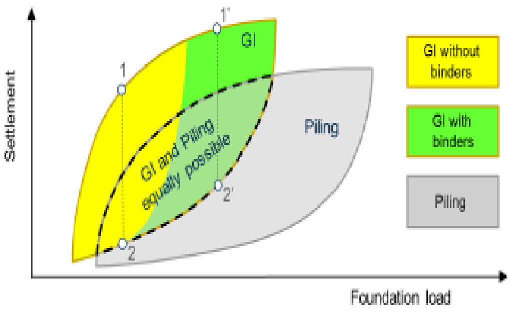

FIG.2.Tentative ranges of piling and ground improvement solutions for foundation support

In this respect, it should be noted that GI solutions usually offer shorter execution times and lower construction costs, and are therefore attractive to clients and contractors. In addition in a lot of situations also a reduction of the project's carbon footprint in achieve as add-on.

6 EXAMPLES OF GEOTECHNICAL OPPORTUNITY MANAGEMENT

6.1. **D-walling and vibro compaction**

The underlying projects involve different ground conditions, structures sensitive to total and differential settlements, and heavily loaded foundations in the form of slabs and separated footings. Densification of a loose cohesionless soil deposit by applying VC is one of the most effective GI methods. Figure 3 illustrates the use of VC to support a high-rise building in Gdynia, constructed behind a gravity-type quay wall.
The area was a dredged zone of backfilled marine sediments in a loose to medium dense state, composed of fine/medium/coarse sands with some silty inclusions in deepest parts of the dredged zone. While the concentrated loads from both towers were mainly taken by purposely located diaphragm walls, the design aimed to optimize the thickness of the foundation slab utilizing subgrade reaction.

To increase ground stiffness below the slab, VC was applied to a depth of 5 to 8 m below the working level. The GI design was based on FEM 3D soil-structure interaction analysis.

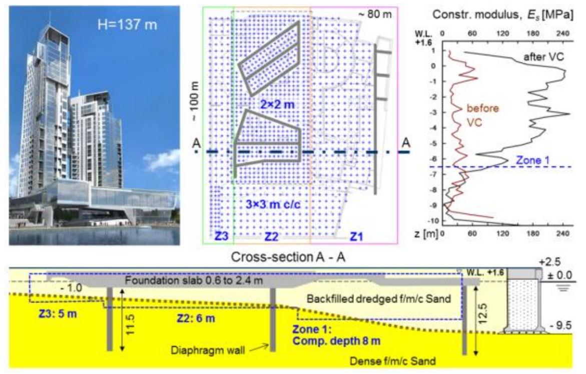

FIG.3.Compaction of dredged soil with VC to enhance slab-subgrade interaction

There was a good agreement between the observed and predicted settlements (Fig. 4) as shown in Fig.4 also.

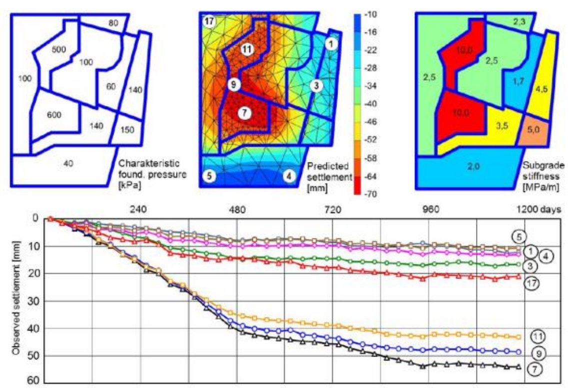

FIG.4. Predicted and observed settlements, Sea Tower foundation slab

The applied scheme was more than three times less expensive than the original solution, and also shortened the construction schedule.

6.2 DSM as Foundation of wind turbines

When deep soil mixing is performed to support wind turbine foundations the external loads can be 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 foundation system is desired. It must be noted that the behaviour of wind turbine foundations is generally governed by a high overturning moment. Consequently, foundation tilt is of major concern as well as the overall stability of the wind turbine, which strongly depends on the position of the centre of rotation.

Depending primarily on the adopted arrangement of DSM columns and on the selected design UCS of stabilised soil, which in general may represent hard to semi-hard material, the improved ground is usually considered as a geo-composite system. Deformation and stability analyses for composite ground are often complex and involve non-linear and stress/strain dependent interaction behaviour. Therefore simplified calculations based on semi analytical methods often need to be cross-checked or supplemented by advanced 3D FE analysis to determine more realistic foundation displacements and stresses acting in individual columns (Topolnicki, M. 2013). Unreinforced and reinforced DSM columns have been used, as shown in Figures 5.

In this case, comprising 98 m high wind turbine with rated power of 2MW, the adopted solution involved 50 unreinforced DSM columns diameter 1.0 m, arranged in two rows along the periphery of a foundation base having a diameter of 17.5 m. To avoid stress concentrations on the trimmed heads of DSM columns, a 50 cm thick sand/gravel cushion has been designed, installed and compacted before application of the lean concrete layer, 10 cm thick. The adopted characteristic compressive strength of soil-mix was 2.3 MPa after 56 days of curing.

The resulting area improvement ratio is thus 23.1%. The transition layer above trimmed DSM columns, also 50 cm thick as in the preceding case, has been constructed using compacted aggregate or cement-stabilised soil. The adopted characteristic compressive strength of soil-mix was 2.2 MPa after 56 days of curing.

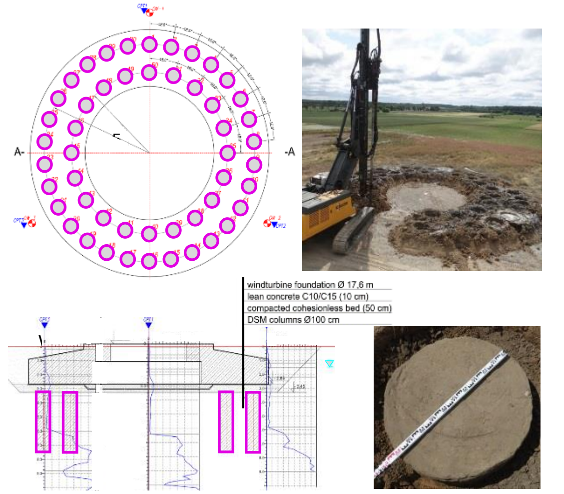

FIG. 5. Wind turbine foundation supported on 50 unreinforced DSM columns diameter 1.0 m (turbine height 98 m)

The second example, presented in Figure 6, illustrates the application of 38 no. unreinforced DSM columns diameter 1.6 m, applied for ground improvement below a circular foundation of 20.5 m diameter, supporting 119 m high wind turbine. The resulting area improvement ratio is thus 23.1%. The transition layer above trimmed DSM columns, also 50 cm thick as in the preceding case, has been constructed using compacted aggregate or cement-stabilised soil. The adopted characteristic compressive strength of soil-mix was 2.2 MPa after 56 days of curing.

Soil mixing was conducted from the bottom of shallow excavations, about 2 m deep. The columns, which were 6 to 8.7m long depending on turbine location, were designed to take maximum compression and tension forces resulting from the adopted loading conditions.

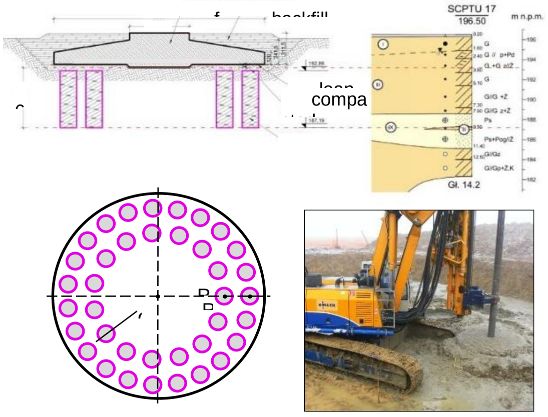

FIG. 6. Wind turbine foundation supported on 38 unreinforced DSM columns diameter 1.6 m (turbine height 119 m)

When a high overturning resistance of wind turbine foundation is required, the DSM columns may be reinforced with steel beams and used in a similar way as compression and tension piles, as illustrated in Figure 7. The adopted solution comprised 40 reinforced DSM columns diameter 1.0 m, positioned in two rows along the periphery of a 16-sided polygon foundation with an average diameter of only 15 m.

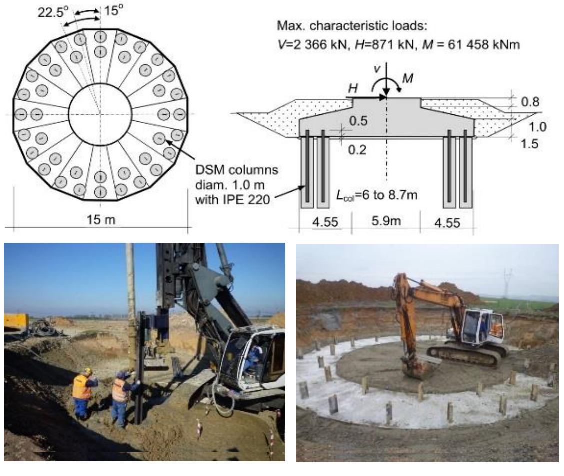

FIG. 7. Wind turbine foundation supported on 40 reinforced DSM columns diameter 1.0 m (turbine height 78 m)

To accommodate for tension forces steel soldier profiles IPE 220, with lengths of 6 to 8 m, were centrally installed in each column just after completion of the soil mixing operation. They extended to a minimum of 0.7 m above the final level of column head, allowing for 0.5 m embedment length in the concrete foundation.

For reinforced columns bond stress of soil-mix must be checked to assure safe transfer of tensile loads to steel solider elements. Taking into account the requirements resulting from compression and tension forces acting on DSM columns, the characteristic compressive strength of soil-mix material in this project was set to 2 MPa after 56 days of curing.

7. CONCLUSIONS

The interaction between the ground conditions and characteristics of the various homogeneous areas and technical project requirements determine the portfolio of geotechnical solutions. The determination of realistic parameters has a decisive influence in this case on the selection of potential geotechnical methods and the possible designs.

The significant challenges for the future in such kind of projects can be summarized with the following bullet points:

- Construction projects are becoming more and more complex,
- Economic optimization requirements will promote cooperation and increasing competition,
- Increasing demand for automation and the automatic monitoring of building processes,
- Clients and site supervisors will expect a more efficient documentation of the processes
- Environmentally-friendly technologies are becoming more attractive.

Creative solutions in use of new or improved technologies as well as the changing and adjusting of existing technologies to suit the specific requirements of the project can contribute to generate an increase in value for the owner.

7 RECOMMENDATIONS

Considering the future challenges as general requirements for changes, innovative solutions could show a way out of this problematic issues. But ingenious alternative solutions require a more precise management of alternative opportunities.

Optimal opportunity management largely depends on the information density and the expertise of the project members and also has a permanent effect on the success of the project. Opportunity management gives the chance to achieve the project scopes for the client by optimizing cost, time and quality. The following recommendations should foster the chance to identify optimal geotechnical solutions:

- Early high quality and extensive investigation on site
- Design using high quality methods
- Detailed planning as part of the process
- Consideration of experience and expertise of people involved in the project
- Early specification of the objectives
- Transparent project information system including risk and opportunity registers

To cope with this more general and conceptual formulation of the task the below summarized capabilities and competences in the organisation handling geotechnical opportunities and creating optimal geotechnical solutions are required:

- deep knowledge of technologies and processes including the limits of application of the different technics
- excellent judgement on subsoil characteristics and stress strain relationships of soil materials
- advanced design capabilities including judgement of design model and approach
- understanding the execution process and the impact of the process
- fair judgement on technical requirements versus products involved

To cope with the recommendations for best opportunity management in addition to the technical skills geotechnical engineers in addition should show capabilities in: planning and organizing, analysing and structuring, should be associated to accuracy and reliability and team work and relationship with colleagues as soft skills to identify optimal solutions with the teams from different disciplines involved in a project. Those geotechnical engineers developing a sound and perfect combination of the technical expertise and the soft competences will be fit for future challenges. As a geotechnical engineer is should be the goal not only to sharpen the geotechnical knowledge but also acquire and shape interpersonal skills.

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