Novel Application of Wet Deep Soil Mixing for Foundation of Modern Wind Turbines

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ABSTRACT: Owing to good experience with the foundations of road bridges and heavily loaded footings supported on DSM columns, some of them being in service for about 10 years, it has been considered to apply DSM technology for wind turbine foundations. Meanwhile, 33 such projects have been successfully completed in Poland since 2007. The adopted execution method and the design procedure, based on FEM 3D calculations, are outlined first, followed by two case histories illustrating the use of unreinforced and reinforced DSM columns, purposely located along the periphery of wind turbine foundation. In the first case a transition layer above the columns is required to avoid excessive tensile forces in soil-mix material. For reinforced columns bond stress of soil-mix must be checked to assure safe transfer of tensile loads to steel solder elements.

INTRODUCTION

In Poland the wet Deep Soil Mixing (DSM) method was introduced in 1999, beginning with construction of cut-off walls along river dikes. Already 2-3 years later probably the first worldwide application of wet DSM for the foundations of 39 bridges across and along the newly constructed A2 highway took place. Following careful soil investigations and analyses it turned out that certain road bridges, originally designed on large diameter piles, could be founded on DSM columns fulfilling all technical requirements with respect to stability and settlement of respective supports. It was also noticed that shorter construction time and lower cost of ground improvement contributed to substantial economical savings compared to piling design. Since then, a broad variety of DSM projects have been conducted, comprising more than 250 road bridges and numerous industrial halls, multi-storey commercial buildings, retaining walls and excavation supports. The DSM method is now seen in Poland as a reliable and widely accepted technology of ground improvement, with probably the highest current use in Europe for foundation engineering purposes.
A good example of on-going development and growing application range of this method of ground improvement is the use of wet DSM for the foundations of modern wind turbines, which began in 2007. Since then 33 wind turbines have been founded on wet DSM columns in Poland, and further projects are pending because the solutions adopted turned out to be reliable, quick in execution and competitive, when compared to other foundation methods. In the following sections the adopted execution method of wet soil mixing and the geotechnical design procedure is shortly presented, followed by two case histories illustrating the applications.

THE ADOPTED METHOD OF WET SOIL MIXING

The wet soil mixing construction equipment consists of a batch mixing plant to supply proprietary slurry, and of a mixing machine for injection and mixing of slurry into the ground. For remote and isolated locations, typical for wind turbines, a suitable water tank is also necessary. The machines usually have one mixing shaft mounted on fixed lead, and can therefore incorporate down pressure capability (Fig. 1). The mixing tool has an assortment of cutting, mixing and shearing blades of full diameter to efficiently break down the soil structure. Steel hard-facing and an arrangement of purposely located teeth serve to aid penetration and reduce maintenance. A small diameter lead auger/drilling bit extends below the cutting blades to centre and control penetration and verticality (Fig. 2a). The injection nozzle is located near the shaft tip, and the centrifugal force helps to distribute the slurry to all parts of the column during rotation. In addition to mechanical mixing, high-velocity jet grouting can be also used in order to reduce penetration resistance and improve mixing operation and/or to increase the diameter of the improved ground, if needed (Fig. 2b).

FIG. 1. (a) Single shaft soil mixing rig in operation, (b) freshly executed DSM column diameter of 1.0 m (in use also 0.6 m to 1.2 m).

The installation process of DSM columns consists of positioning the mixing shaft above the planned column location, penetration of the mixing tool, verification and
improvement of the bottom soil layer, withdrawal, cycling up and down with reduced slurry delivery rates, usually up to 3 times, and movement to a new location. Restroking over the full depth is beneficial in the case of interchanged soft/stiff layers and stratified subsoil, leading to more uniform properties of stabilised soil also across the depth of treatment.

The accompanying delivery of the stabilising agent to the subsoil is operator/computer controlled. Normally, about 50 to 70% of the total slurry volume is used during first penetration. Pumping rates typically range from 0.08 to 0.3 m³/min, depending on column diameter, rate of penetration and distance to rig.

**THE DESIGN PROCEDURE**

The design procedure of soil mixing applications usually involves two steps, i.e.: (1) selection of the design compressive strength of stabilised soil, the so-called soil-mix design, and (2) adoption of a suitable column pattern, often referred to as the geotechnical design (e.g. Massarsch and Topolnicki, 2005).

The soil-mix design is usually based on laboratory test results involving a soil specimen mixed with different cements of component binders, or can be based on accumulated experience and field strength data obtained from completed projects. The expected unconfined compressive strength (UCS) of stabilised soil is usually selected in relation to physical and chemical characteristics of treated soil and groundwater, type and amount of cement and other relevant working specifications, such as water/cement ratio and applied mixing work. At this stage a good understanding of the intricacies of soil-cement physics, chemistry and mechanics is required in view of the variability of soils, binders and mixing procedures.

The geotechnical design is aimed to determine the final installation pattern and dimensions of improved ground on the basis of relevant Ultimate Limit States (ULS)
and Serviceability Limit State (SLS) analyses to satisfy functional requirements of wind turbine manufacturers. 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. A common feature of such a system is that untreated soil is surrounding an individual column or a column group, or is left within enclosed spaces formed by stabilised soil. As a result, the interaction between the stabilised and the native soil must be carefully considered and understood at the stage of design.

Deformation and stability analyses for composite ground are generally very complex, and advanced 2D or 3D FEM calculations are indispensable, as presented in the following section. It must be also 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, as illustrated in Fig. 3 for a typical shallow foundation and a combined solution, involving supporting inclusions in the form of DSM columns arranged along the foundation periphery.

![FIG. 3. Failure modes for a shallow foundation (a) and combined foundation system with peripheral DSM columns (b).](image)

The verification of soil-mix material internal stability is based on the allowable stress concept. The allowable UCS of soil-mix, \( f_{ca} \), is thus calculated as \( f_{ca} = \frac{f_{ck}}{F_s} \), where \( F_s \) is the adopted safety factor. Since \( f_{ca} \) is based on UCS in which no account for dynamic loading is incorporated, a relatively high safety factor of 3 or more is typically used in combination with extreme characteristic loading.

**SELECTED CASE HISTORIES**

**Foundation Support with Unreinforced DSM Columns**

A 78m high wind turbine, with rated power of 2 MW and square foundation footing of 16.5×16.5m, was located on unfavourable ground conditions. The subsoil consisted of sandy clays of varying plasticity to the depth of –7.5m and of underlying compacted fine/medium sands and clayey sands. The clay found below the foundation level and extending to the depth of –4.4m was in a plastic state and had a...
liquidity index, $I_L$, of about 0.35 to 0.45. The underlying clay was stiffer, with $I_L$ between 0.20 and 0.30.

The design requirements for the foundation system included two criteria, i.e. the dynamic rotational stiffness, $k_{p,\text{dyn}}$, should exceed 60,000 MNm/rad and the maximum relative foundation tilt, $\Delta s/B$, should be less than 3 mm/m during 20 years of operation. The conducted calculation check indicated, however, that without any ground improvement measures the square footing is likely to settle 39.7 mm on the active side and heave 19.5 mm on the passive side when loaded with an overturning moment of about 52,000 kNm, (Fig. 4). Such deformation would correspond to relative tilt of 3.6 mm/m, thus exceeding the design criterion.

![FIG. 4. Foundation tilt in case of unimproved ground (scaled 50 times).](image-url)

In order to improve turbine stability a novel foundation concept was therefore proposed, involving the use of 88 unreinforced 0.8 m diameter DSM columns, positioned in two rows along foundation periphery on a center-to-center spacing of 1.25m (Fig. 5). The columns were installed through the soft clay layer and penetrated about 1.0m into the underlying stiffer clay. They were designed as settlement reducing elements, improving rotational stability of the turbine foundation. Above the heads of trimmed columns a transition layer of 0.4m thickness was provided. Soil mixing was conducted with water/cement slurry of 1.6 relative density. Average cement consumption was 320 kg/m$^3$ of treated soil, with the use of composite Portland cement CEM II/B-M (S-V) 32.5R, containing 67 to 79% of clinker, 21 to 35% of silica fly ash (V) and granulated blastfurnace slag (S), and 0 to 5% secondary additives.

The geotechnical design of this project, which was completed in 2007, has been recently back analysed with an improved PLAXIS 3D code. Contrary to the initial modelling attempt with square pile-like supporting elements, the DSM columns have now been represented as truly cylindrical members with interface elements to account for better assessment of shaft friction and base bearing capacity of short-length inclusions. The columns were represented with volume type FE elements, applying linear-elastic model for soil-mix material ($E=714$ MPa, $\nu=0.2$).
FIG. 5. Foundation system with 88 unreinforced 0.8 m diameter DSM columns.

The calculated vertical displacements indicate partial settlement and non-symmetrical rotation of the foundation footing, with associated total tilt of about $\Delta s = 25.6$ mm (Fig. 6). Consequently, the relative tilt equals to $\Delta s/B = 1.6$ mm/m and is well below the allowable limit of 3 mm/m. Corresponding dynamic rotational stiffness of the foundation is 162,800 MNm/rad. The maximum compressive stress on the soil at the foundation level and above the corner DSM column is about 250 kPa.

Max. characteristic loads:
- $F_x = 726$ kN
- $F_y = 22$ kN
- $F_z = 2355$ kN
- $M_x = -3410$ kNm
- $M_y = 51841$ kNm
- $M_z = 1122$ kNm

FIG. 6. (a) Vertical displacements after ground improvement, (b) corresponding vertical stress at the foundation level.

The maximum characteristic compressive force, acting on a single column on the active foundation side, is about 170 kN, corresponding to an average compressive stress of 170/0.5 = 340 kPa. The maximum tensile force acting on a single column on the passive side is about 33 kN, corresponding to an average tensile stress of 66 kPa.
Limited tensile stresses in DSM columns can be accommodated by soil-mix tensile strength, usually in the range of 0.15×UCS (cf. Topolnicki, 2004).

Allowing for sufficient safety with respect to design assumptions, acting loads, adopted mechanical parameters of native and stabilised soil and modelling accuracy the maximum characteristic column load was originally set to 350 kN. With a material safety factor of $F_s=3.0$ this lead to a required compressive strength of the stabilised soil after 56-days of curing of at least $350\times3/0.5=21$ MPa. Control uniaxial compressive tests, conducted on 24 cubic samples of 15×15×15 cm formed from wet grabbed material, yielded a mean UCS of 5 MPa after 28 days of curing, which exceeded design expectations.

More detailed FEM 3D back analysis has revealed that soil-mix material with the adopted UCS is also fully capable of accommodating local compressive and tensile stresses developing on the column periphery, which can be slightly higher than the computed average stresses (Fig. 7). Skin tensile stresses result from a very small relative upward movement of the soil with respect to more stiffer DSM columns. This kind of mechanism develops in case of relatively short columns which move upwards when the foundation is loaded with a maximum overturning moment. For longer columns a shearing mechanism is more likely to develop.

![FIG. 7. Vertical stress in model DSM columns.](image)

**Foundation Support with Reinforced DSM Columns**

The project comprised the foundations of 15 wind turbines, each 78m high and with a rated power of 2 MW, located in the south-western part of Poland. The superficial loess-type soils, consisting of silty clays and silts with compression modulus between 4 and 5.5 MPa, extended to the depth of 3 to 10m below ground
surface, depending on turbine location. These soils were underlain by relatively well-compacted fine and medium sands, with a relative density of 0.6 to 0.7, or by stiffer silty clays, with a liquidity index between 0 and 0.17.

Noting the requirements for allowable foundation tilt ($\Delta s/D \leq 3$ mm/m), dynamic rotational stiffness ($k_{\phi,\text{dyn}} \geq 25,000$ MNm/rad) and total settlement ($s \leq 20$ mm) a shallow foundation method for all turbines was excluded and the use of wet soil mixing was recommended. The adopted foundation solution comprised 40 reinforced DSM columns diameter 1.0m, positioned in two rows along the periphery of a 16-sided polygon foundation with an average diameter of only 15m (Fig. 8).

\[
\begin{align*}
\text{Max. characteristic loads:} \\
V &= 2366 \text{ kN}, \\
H &= 871 \text{ kN}, \\
M &= 61458 \text{ kNm}
\end{align*}
\]

**FIG. 8.** Foundation system with 40 reinforced DSM columns.

Soil mixing was conducted from the bottom of shallow excavations, about 2 m deep (Fig. 9). 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. To accommodate for tension forces

\[
\begin{align*}
L_{\text{col}} &= 6 \text{ to } 8.7\text{m} \\
4.55 &\quad 5.9m &\quad 4.55
\end{align*}
\]

**FIG. 9.** (a) Installation of steel profile, (b) completed DSM columns.
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 a minimum of 0.7 m above the final level of column head, allowing for 0.5 m embedment length in the concrete foundation.

The results of FEM calculations with PLAXIS 3D for a selected turbine with 6 m long columns are shown in Fig. 10. Contrary to the previous case history, the modelled DSM columns were fully "attached" to the concrete foundation cap to allow for a direct transmission of resulting compression and tension forces. Estimated relative foundation tilt for extreme characteristic loading was $\frac{\Delta s}{D}=2.1$ mm/m and the dynamic rotational stiffness was $k_{\text{proj, dyn}}=303,692$ MNm/rad, both fulfilling design criteria. The largest characteristic compression force in a DSM column was found to be in the range of 380 to 460 kN, equivalent to a maximum design compressive stress in soil-mix of 586 kPa. Consequently, the required UCS of soil-mix should be above 1.8 MPa, with a material safety factor of 3.

![FIG. 10. (a) Deformed mesh, scaled 50 times, (b) foundation settlement.](image)

The maximum calculated tension force, to be taken by steel reinforcement, was 270 kN. The resulting bond stress for a steel profile IPE 220, with a periphery of 0.848m and minimum length of 5.3m inside the DSM column, is $f_{bd}=62$ kPa. With a partial safety factor of $\gamma_c=3$ such a bond stress would require a soil-mix material with a design compressive strength of minimum $(3\times0.062/0.36)^2=0.27$ MPa, which in turn would lead to a necessary UCS of stabilised soil exceeding $3\times0.27=0.81$ MPa.

Taking into account both requirements, resulting from compression and tension forces acting on DSM columns, the design of soil-mix material was set to yield a UCS≥2 MPa after 56 days of curing.
CONCLUSIONS

Growing international utilisation of DSM demonstrates that this technology can be used with technical and economic success against other competitive solutions of ground improvement and foundation engineering. With respect to wind turbine foundations the accumulated experience with the use of wet soil mixing is so far restricted to 33 individual applications. Therefore further projects and observations are needed to establish workable procedures and accepted standards. Bearing this in mind it should be noticed, however, that the design and execution practice outlined above is already supported by 10 years of experience related to the foundation of more than 250 road bridges on DSM columns, where similar loading conditions occur and where the observed performance has widely corroborated design predictions. Nevertheless, a good understanding of possible failure modes is essential when dealing with foundations supported on DSM columns which have relatively small size and are loaded with high overturning moments and horizontal forces.

When 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 ground improvement is desired. The choice of the required strength of cemented soil and of the load transfer system adopted is dictated by functional requirements and associated design criteria. In all cases the quality of load-bearing columns is essential to prevent progressive failure mechanisms. Consequently, a good assessment of the expected strength and deformation properties of the stabilised soil is one of the key issues in reliable and optimum DSM design. Stiffer columns interact in a different way with the soil than the more flexible columns. It is therefore important to account for these differences in respective geotechnical analysis, as pointed out by Wehr and Sondermann, 2011.

Similarly, high QC and QA standards, closely related to individual project requirements and in line with the European Standard EN 14679 are required with respect to conducted DSM works, including field loading tests, if necessary.

REFERENCES