Soil mixing - challenges of applications ranging from ground improvement to structural elements

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ABSTRACT
The current state of development of the wet method of deep Soil Mixing (SM) is presented, based on experience gained in Poland, where the use of wet SM is seeing continuous growth which begun in 1999. Considered case histories refer to ground improvement, foundation support, retention systems and cut-off walls. They demonstrate not only a unique flexibility of the application of SM, but also prove that deep soil mixing should be considered as a competitive solution to a number of different geotechnical problems. Challenges of SM application are connected with varying properties of the stabilised soil, as well as with appropriate geotechnical design. Stiff, rigid SM columns interact in a different way with the soil than the more flexible columns. It is therefore important that design engineers are aware of these differences. Specialised soils mixing in relation to environmental projects is not touched upon.

Keywords: soil mixing, ground improvement

1 INTRODUCTION
The use of in situ Soil Mixing (SM) in Europe to improve the engineering properties of soft or contaminated ground is increasing rapidly, indicating growing interest and acceptance of this relatively new technology in civil engineering. The extent of applications of SM across European countries differs considerably, as reviewed recently by Massarsch and Topolnicki (2005). Outside Scandinavia the total number of implemented projects is still relatively small compared with other relevant geotechnical methods, however industrial, social and environmental developments in Europe offer major commercial opportunities for an increase in SM applications. In Poland, for instance, the wet soil mixing method is now in regular use.

Typical applications of SM involve ground improvement and hydraulic cut-off walls. However, structural supports, such as pad and strip foundations and retaining structures, have also been founded on soil mixing elements installed in various patterns ranging from individual columns to grids, walls and blocks of stabilised soil (e.g. Topolnicki, 2004). Consequently, the strength of soil mixing elements may differ significantly within the range determined by low capacity columns, with a compressive strength of about 0.3 to 0.5 MPa, and high capacity individual or combined structural elements, having unconfined compressive strength in the order of 2 to 5 MPa, which perform similar to piles or block foundations. 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 mixing method used.

In the following sections, selected examples of soil mixing applications are presented to illustrate the current practice, based on the experience gained in Poland, where the use of wet soil mixing has grown rapidly since 1999. Considered case histories refer to ground improvement, hydraulic cut-off wall, support of slab and individual foundations and retention systems. They demonstrate not only a unique flexibility of the application of SM, but also prove that deep soil mixing should be considered as a competitive solution for a number of different geotechnical problems.
2 APPLICATIONS

2.1 Ground improvement for city highway

SM columns of diameter 0.8 m were applied to support a road embankment overlying weak soils found to the depth of 3 to 8 m below the ground surface (Fig. 1). The subsoil consisted of loose anthropogenic fill, underlined by peat and organic clay. The organic soils were 1 to 4 m thick. The embankment height was 1.3 to 2.5 m and the equivalent live load was 30 kPa. A triangular column spacing of 2m×2m was selected, resulting in the design compressive stress of 480 to 676 kPa, assuming column diameter reduced to 0.7 m. The required unconfined compressive strength (UCS) of the stabilised soil material was 1.5 MPa. Altogether, 2402 columns with a total length of 15,532 m were constructed. The final embankment was strengthened with two layers of geogrid, resulting in the so-called Load Transfer Platform design (cf. Topolnicki, 1999).

2.2 Hydraulic cut-off wall

A hydraulic cut-off wall is constructed by installing intercut SM columns to intercept potential seepage flow paths. Since the hydraulic conductivity and continuity of the cut-off wall are the most important design considerations, the slurry mixes must be tailored to soil conditions, and adequate control of columns’ overlapping zones and verticality are required. This is especially important when cut-off walls are executed to a large depth with single shaft mixing equipment, as shown in Fig. 2.

For SM cut-off walls, the unconfined compressive strength is typically in the range of 0.7 to 3 MPa, and even higher if steel reinforcement is installed. 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 the associated decrease of the unconfined compressive strength usually below 1 MPa.

2.3 Support of a slab foundation

A multistory building was located in heterogeneous soil conditions. Under superficial mixed fill, organic clay and some peat were locally present, extending from 3.5 to about 6.7 m below the foundation level. Organic soils were underlined by fine sand and silt layers of varying thickness, making ordinary piling very expensive due to the necessary pile length. Early calculations also indicated, that direct placement of the foundation slab on the existing soil would lead to large and unequal settlements, ranging from 7 to about 50 cm.

In this situation a wet SM option was investigated and finally accepted by the client. The design was based on 3D FEM calculation, allowing for slab-soil interaction and elastic behavior of columns. The resulting arrangement of 461 SM columns is shown in Fig. 3. For the outlined design it was essential to make a good estimate of the expected compressive strength of the stabilised soil since significant variation in column strength was anticipated. For this reason, maximum factored load acting on a single column was limited to 430 kN, resulting in design compressive stress of 0.86 MPa, and a special mixing procedure was adopted at the construction site. With a safety factor of 2.5, applied to the maximum factored design stress, the 28-days UCS of the stabilised soil was required to be 1.9 MPa.

2.4 Support of strip and pad foundations

Strip and pad foundations of a commercial centre Megaplex were initially designed for CFA piles because excessive settlement differences were expected. The subsoil consisted of a thin fill material, underlying sandy and silty clays, and a coarse sand layer in a dense state. Loads acting on strip foundations ranged between 230 and 729 kN/m, with resulting vertical stresses of 230 to 430 kPa. Twelve types of rectangular footings were also designed for loads between 1170 and 5670 kN, yielding vertical stress of 310 to 677 kPa (Fig. 4).

The initial piling design was successfully converted into a competitive SM project. Pad and strip foundations were supported on closely spaced SM columns of 0.8 m diameter, and were consequently designed as direct foundations, resulting in cost savings since less steel reinforcement was needed. The number of columns under the footings ranged from 3 to 14, and was determined by taking into account the expected strength of the stabilised soil as well as the allowable settlement difference of 5mm over 6 m span, specified by the client. The maximum design load acting on a single column, with slightly reduced diameter due to aggressive groundwater, was limited to 512 kN, corresponding to compressive design stress of 1330 kPa. Exposed columns on the bottom of foundation pits are shown in Fig. 5.
Figure 1. Road embankment supported on SM columns (Trasa Zielona, Lublin, Poland).

Figure 2. Soil mixing cut-off wall to intercept seepage flow paths under river bank embankment (The Vistula river near Tarnobrzeg, Poland).
Figure 3. Arrangement of SM columns under the foundation slab of multistory building (Kielce, Poland).

Figure 4. Arrangement of SM columns under pad foundations of a commercial centre (Megaplex, Katowice, Poland).

Figure 5. Exposed SM columns under pad foundation of a commercial centre (Megaplex, Katowice, Poland).

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Figure 6. Soil mixing works and exposed columns for a bridge support foundation (A2 highway near Poznań, Poland).

Figure 7. Temporary SM wall with embedded steel H-beams for excavation support (Music Academy, Poznań, Poland).

Figure 8. Permanent soil mixing retention wall with embedded steel H-beams and concrete facing (Oświęcim, Poland).

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2.5 Bridge supports

Construction work on the A2 highway in Poland led to interesting applications of wet SM. Careful analysis revealed that certain road bridges, originally designed on large diameter piles, can be supported on SM columns, fulfilling all stability and settlement requirements and offering substantial savings on foundation costs.

The solution adopted for bridge WD-23 provides a good example of this application. The subsoil consisted of boulder sandy clays, with an average CPT cone resistance of 2 MPa. The geotechnical design included a total of 200 columns for the five bridge supports. The applied arrangement of 46 SM columns under bridge abutment foundation is shown in Fig. 6. The allowed maximum characteristic design compressive stress was 830 kPa, and the requested compressive strength was 2.5 MPa. The observed settlement of this support was 12 mm. It is interesting to note that since 2002 about 80 road bridges have been founded on SM columns in Poland.

2.6 Temporary and permanent retention systems

Retention systems using SM are mostly comprised of applications associated with restraining the earth pressure mobilised during deep excavations. In these applications wall-type column patterns are used, while the soil-cement mix is typically engineered to have high strength and stiffness. To overcome soil and water lateral pressures the SM columns should also have adequate 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.

For the projects shown in Figs. 7 and 8, steel H-beams were installed in fresh SM columns to increase the bending resistance and create a structural wall for excavation support. Elongated mixing time and full restroking were required to ensure easier installation of soldier elements immediately after mixing. Panels of mixed soil between H-beam reinforcement were designed to work in arching. Tieback anchors or stage struts are typically used in combination with the SM walls. In case of circular excavations or shafts peripheral concrete cap beams working in hoop compression can be constructed instead, as shown in Fig 7.

For permanent SM walls, concrete facing is needed to prevent the soil-cement mix from long-term deterioration and damage and to provide smooth wall surface. Concrete facing is easily constructed, with the reinforcing bars welded to exposed H-beams, as shown in Fig. 8.

3 CONCLUSIONS

When soil mixing is applied to support shallow embankments or foundation slabs usually to reduce excessive or differential settlement, the quality of individual columns is less important and the overall performance depends mainly on the combined interaction between the supported structure, soil, and strengthening elements (i.e. columns). This soil-structure interaction design concept is frequently applied in the case of low strength soil mixing and is often combined with preloading to accelerate strength gain and consolidation settlement. This concept has proved to be efficient and cost-effective. On the other hand, when soil mixing is performed to support high embankments or heavily loaded pad or strip foundations, and where horizontal loads, shear forces, or bending moments may appear, the quality of load-bearing columns is essential to prevent progressive failure mechanisms. The same applies for economically attractive low values of the area improvement ratio, and for retention systems with steel reinforced soil mixing columns. 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 SM design. Stiff, rigid columns interact in a different way with the soil than the more flexible columns. It is therefore important to account for these differences in the geotechnical design of Soil Mixing.

REFERENCES

