LIME CEMENT MIXING (LCM) – APPLICATIONS OF THE SCANDINAVIAN METHOD

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ABSTRACT

Since the introduction of the Scandinavian Lime/Cement Column Method of Soil Mixing (LCM) in the late sixties and early seventies, applications have experienced a major increase. Experience from different applications in Scandinavia and the United Kingdom is presented in this paper. Considered case histories refer to ground improvement, foundation support for light buildings, support for temporary sheet pile walls, permanent application to reduce the active earth pressure behind a mass gravity wall and support for deep excavations. The applications demonstrate the flexibility of the LCM method, which can be applied as a competitive solution to a number of different geotechnical challenges.

1 INTRODUCTION

In situ Soil Mixing (SM) is rapidly increasing in Europe as a method for stabilising soft soils to increase the engineering properties. Soil Mixing is a widely used name and the applications, installation methods and design issues have major differences. The differences and applications have recently been reviewed by Massarsch and Topolnicki (2005). This paper will focus on Soil Mixing using the Scandinavian Dry Deep Mixing (DDM) Method, also known as Lime/Cement Column Mixing (LCM).

The Scandinavian method was originally developed in Sweden in the late sixties and early seventies by Prof. B. Broms and engineer K. Pause (Bredenberg *et al*., 1999). The first equipment used for production of DDM Columns was developed by LCM´s predecessor company, the Swedish contractor BPA in 1976. Figure 2 shows a later model of the installation equipment.

LCM columns were originally developed for foundations of light buildings and for the reduction of settlements in low embankments and parking lots resting upon very soft inorganic clays. In the early projects the mixing additive was quick lime with a typical dosage of 60 kg/m^3 to 90 kg/m^3, the column diameter was 500 mm with a typical column depth of up to 10 m. The design undrained shear strength ($c_{u,col}$) ranged from 60 kPa to 100 kPa. Early development was focused on larger diameter columns, deeper columns, higher strength columns and increased production. Typical column diameters today are 600 mm to 800 mm and maximum installation depth is approximately 25 m. The design undrained shear strength ($c_{u,col}$) is today in the range of 100 kPa to 200 kPa (limited to a maximum of 150 kPa in stability analysis). New additives and mixtures of additives have been used. These are commonly blended as a combination of cement, quick lime, blast furnace slag or fly ash. New additives, various column diameters and more powerful equipment have developed a larger range of applications where LCM columns are applicable.

Typical main applications of LCM columns today are:

- Soil improvement for road and railroad embankments on soft soils.
- Improvement of stability.
- Foundation of houses and light warehouses.
- Reduction of ground vibration.
- Mass treatment of very soft soils such as peat, gyttja (a Scandinavian soil with very high organic and moisture contents) and dredged marine sediments.

Other applications include:

- Increase of passive and/or reduction of active earth pressure for sheet pile walls and retaining systems in soft clay.
- Preventing liquefaction in seismic hazard areas.
- Solidification and remediation work on contaminated soil.
- Support for temporary working platforms.

In the following section, selected examples of applications where LCM columns have been constructed are presented and illustrated. The examples are based on experience on LCM-columns in Scandinavia and the United Kingdom. The considered case histories refer to ground improvement for road embankments, foundations for houses on a uniform floor slab, support for temporary sheet pile walls to reduce the active earth pressure behind a mass gravity wall and as support for a deep excavation. The applications demonstrate that Soil Mixing using LCM-columns can offer a competitive solution for a number of different geotechnical applications.

2 APPLICATIONS

2.1 GROUND IMPROVEMENT FOR A ROAD EMBANKMENT

LCM-columns of 600 mm and 800 mm diameter were applied to support a road embankment overlying very soft and soft clay and partly peat. The soft clay had typical undrained shear strengths of 12 kPa to 25 kPa and a thickness of 5 m to 20 m.

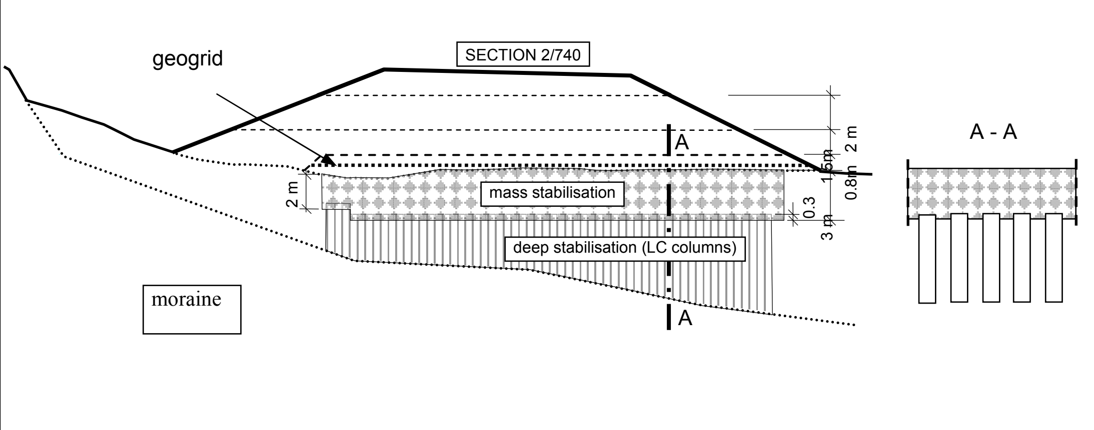

Figure 1: Cross section of a road embankment stabilised with DDM and mass mixing (Moraberg, Sweden, 2004).

On a section of approximately 500 m of the embankment, 0.5 m to 2.6 m of peat overllay 0.3 m to 0.5 m of gyttja above the soft clay deposit. The peat deposit had a typical water content of 500-1200% and the gyttja deposit had a typical water content of 100% to 300% and undrained shear strength of 3 kPa to 7 kPa. Mass treatment (so called mass stabilisation) was used in the peat and gyttja deposits.

In the soft clay LCM-columns were installed to a maximum depth of 15 m, acting as floating columns, on a square grid of between 1.0 m and 1.8 m centres depending on the height of the embankment. In areas where the factor of safety (FOS) was less than 1.0 for the untreated embankment, the columns were installed to interlock, with a spacing of 0.7 m between the columns (0.1 m overlapping), in perpendicular panels under the embankment. This increased the shear resistance and provided a FOS of 1.5. Single columns are sensitive to horizontal forces, hence the installation of interlocking columns to form panels. The additive used was a quick lime and standard Portland cement blended 50/50, and a dosage of 90 kg/m^3. Design undrained shear strength of the columns was 150 kPa (UCS=0.3 MPa). In stability analysis the design undrained shear strength was limited to 100 kPa. Drained parameters were evaluated as an internal friction angle $\varphi'_{col}=35^{o}$ and cohesion $c'=0.35*c_{u,col.}$ In the LCM columns the Young's modulus in the columns was calculated as 30 MPa increasing to 80 MPa at depth. Altogether 16,200 columns with a total length of 119,850 linear metres were installed. Construction of the embankment started 2 weeks after the columns had been installed.

In the part of the embankment where peat and gyttja were overlying soft clay, mass soil treatment was also performed to reduce future settlements and increase the compressive strength in the peat and gyttja deposits.

Installation of single columns in soils with low effective stress such as in peat and gyttja is not recommended as the bearing capacity of single columns is depending on the support from the confinement in the soil deposit. Standard Portland cement was used as additive with a dosage of 175 kg/m^3 in the mass treated soil volume. Design undrained shear strength was 50 kPa in the mass treated soil block. Directly after mixing an early embankment load of crushed stone of 0.8 m was placed on the mass treated soil volume. Between the mass treated soil volume and the embankment fill a geotextile was placed to separate the crushed stone (fraction 0-100 mm) from the mass treated soil. One to two months after the first load was applied a second load increment step to the full embankment height of 2 m was placed (Figure 1). Settlement was measured by horizontal inclinometers.

Measured settlements in the mass treated soil volume supported by underlying LCM columns were in the range of 150 mm cm to 350 mm during the construction time of 1.5 years, with 60% to 80% of the settlement developed within the first month. Measured settlements in soft clay stabilised with LCM columns were in the range of 50 mm to 100 mm during the construction time of 1.5 years. Quality assessment using Column Penetration Tests (CPT) showed an undrained shear strength in the columns of 150 kPa to >400 kPa. In the mass treated peat and gyttja undrained shear strengths varied between 25 kPa to 100 kPa, with an average of 75 kPa.

Figure 2: LCM rig and mass mixing rig at Moraberg (2003).

Settlements have been measured 2.5 years after the road was opened for traffic the measured settlements were <30 mm in all eight measured horizontal inclinometers in both mass treated and column treated areas.

2.2 LCM COLUMNS SUPPORTING SLAB FOUNDATIONS

A 52 house development in Gothenburg, Sweden, was located in an area with deep soft clays, locally extending to >30 m. Piling costs for the building were prohibitive and LCM columns provided an economical solution for the foundations. The soil conditions were typically a 1 m dry crust clay overlying very soft clays, increasing to soft and medium soft clays at depth. The top 5 m to 8 m of the very soft clay was normally consolidated (OCR~1.0), at greater depth the soft clay became over-consolidated with the OCR increasing with depth.

Analysis was performed of the current and proposed stress distributions, where the additional load of 13 kPa from the houses was considered. The analysis showed that with the additional load the effective stress situation at 10 m depth had an OCR=1.25. At OCR≥1.25 creep settlement can be neglected. Therefore the solution adopted was to transfer the load from the houses by using LCM columns to depths greater than 10 m to provide a technical and economical solution as an alternative to friction piles.

DDM columns with a diameter of 500 mm were selected as the solution to transfer the additional stresses from the houses to 10 m depths. The spacing between the columns varied depending on the load situation from the floor slab. For each house an average improvement ratio of a=0.196 (or 19.6%) was adopted. The maximum design load on a single column was limited to 40 kN, corresponding to a compressive strength of 205 kPa, including a safety factor of 1.8. The Young’s modulus in the columns was calculated as 24 MPa at 1 m depth, increasing to 42 MPa at 10 m depths due to increased confinement at depth.

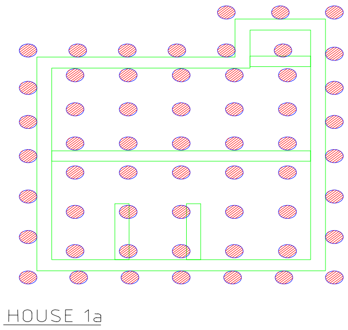

Figure 3: Column layout for a typical house (Hildedal, Gothenburg, Sweden).

The compression modulus M_L in the very soft and soft clay deposit was 0.25 MPa to 0.38 MPa. The combined compression modulus in the stabilised soil volume with an improvement ratio of 0.196 was calculated as 4.8 MPa at 1 m depth increasing to 8.4 MPa at 10 m depth. The calculated settlement was 25 mm for the stabilised 10 m soil volume. The additive used was a 50/50 lime/cement blend and a dosage of 100kg/m^3. 2824 Columns were installed for the 52 houses.

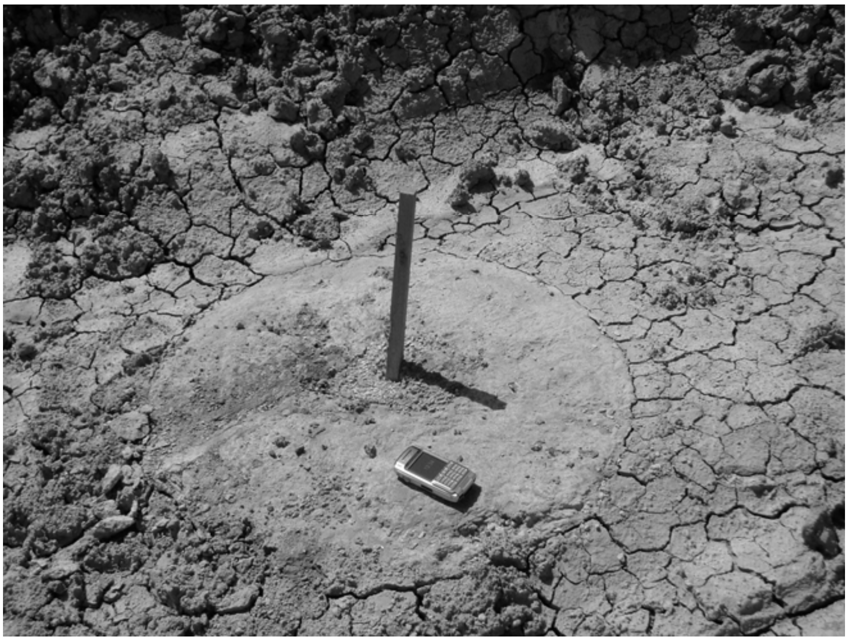

Figure 4: Exposed DDM-column.

2.3 SUPPORT FOR TEMPORARY AND PERMANENT RETAINING SYSTEMS

Retaining systems, predominantly sheet pile walls, can effectively be supported by DDM columns in order to reduce the active earth pressure and/or increase the passive earth pressure. In the last 5 years several of these applications have been effectively used in Scandinavia and United Kingdom.

Columns installed on the passive side (Figures 5 & 6) support the sheet piled wall by increasing the passive earth pressure. As a result of the installation of the LCM columns the shear strength in the soil volume increases. Due to increased undrained shear strength $c_{u,col}>c_{u,soil}$, there is an increased cohesion $c'_{col}>c'_{soil}$ and increased friction angle $\varphi'_{col}>\varphi'_{soil}$. To support a retaining structure columns are installed in panels or blocks perpendicular to the retaining wall system. Other vital requirements for successful support are a high degree of homogeneity in the columns and sufficient interlocking between the columns to transfer the load through a panel or block.

The column panels or blocks increase the average shear strength in the soil volume on the passive side, which increases the passive earth pressure acting toward the retaining structure. There are several advantages provided by installing passive columns: panels, together with a 100 mm to 200 mm concrete slab can usually reduce one level of anchors for the retaining structure. Buildings with a basement can be founded on the LCM-columns as a compensation foundation. The risk for bottom heave also decreases, due to increased shear strength in the soil block.

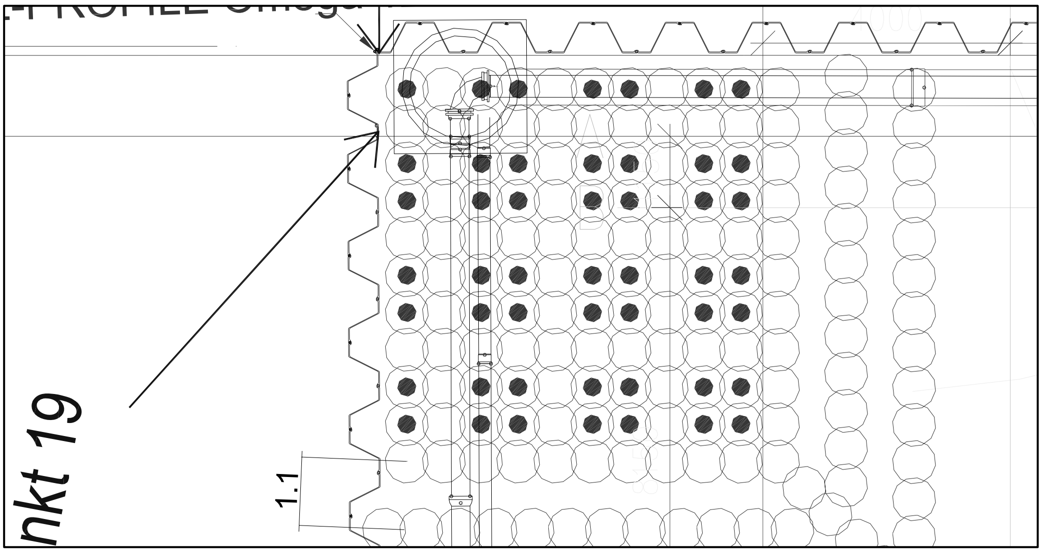

Figure 5: Plan drawing for LCM-columns to passive support a sheet pile wall at Sörkedalsvien in Oslo, Norway.

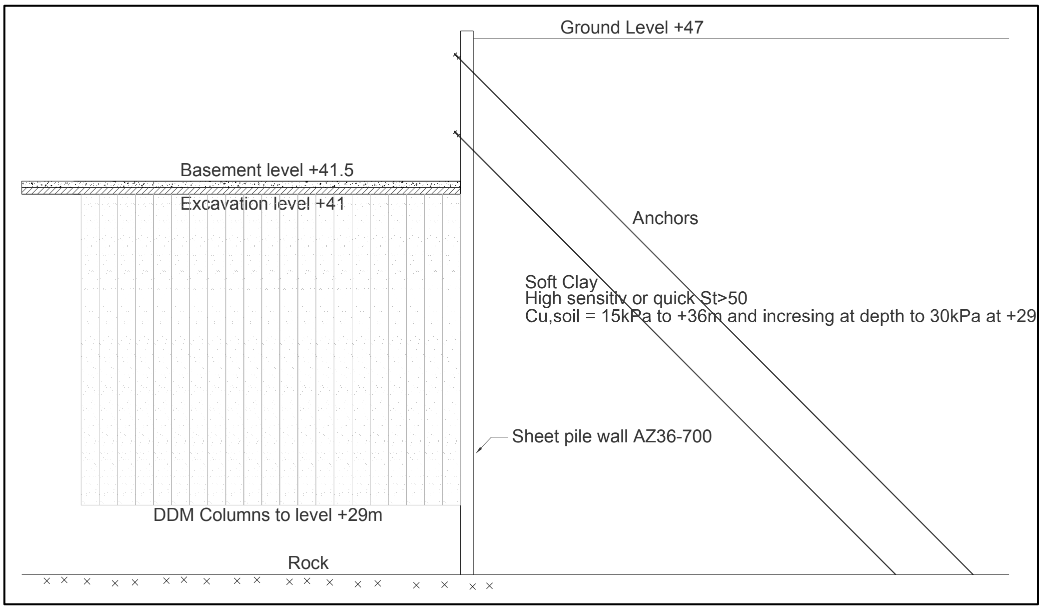

Figure 6: Cross section passive support to sheet pile wall at Sörkedalsvien in Oslo, Norway.

In Oslo, Norway, a deep excavation in a highly sensitive soft clay, at depth becoming quick S_t>50, was supported by a sheet piled wall. The excavation depth was approximately 6 m. The soil conditions were typically 0 m to 3 m of fill overlying 2 m to 3 m of soft clay overlying 5 m to 15 m of very soft and highly sensitive clay improving to soft at depth.

A system of interlocking columns installed in panels perpendicular to the sheet piled wall was submitted. In the corners a high degree of improvement was needed. Therefore a block of columns were installed (Figures 5 & 6). Depending on the excavation depth the improvement ratio in the stabilised soil volume varied between 31% and 57%. In the corner a zone with 100% improvement was needed.

The columns had a diameter of 0.7 m and were installed in 15 m long panels with a 0.1 m overlap to the underlying morain, or to maximum 13 m under the excavation level. The increased passive support from the panels together with a 200 mm concrete slab reduced the number of tieback anchors from 3 levels to 2 levels and at the same time reduced the dimensions of the sheet pile wall.

Figure 7: Installation of LCM Columns for passive support on a sheet pile wall in Asker, Norway.

Similarly, in Barking, London, LCM columns were used to support an existing quay wall in poor condition. As the existing wall was partially continuing to perform its function, it was decided to retain the wall and build a new wall unit immediately behind. The newly formed wall would be independent of the existing wall. The site lies upon geologically recent alluvial deposits of the River Roding. overlying Eocene deposits of London Clay. LCM columns were installed perpendicularly and alongside the existing quay wall to form a mass gravity structure for support. Two vertical panels of 800 mm diameter columns were installed nearest to the existing wall to an average depth of 7 m. Behind the front panels six inclined columns in panels with a centre spacing of 1.4 m between the panels to an average depth of 7 m were installed. Between the inclined panels an interlocking vertical column was installed to support a tieback rod, supporting the existing wall face.

Figure 8: LCM mass gravity block behind existing quay wall at Barking, United Kingdom

The poor condition of the existing wall was assumed to be an imminent risk of failure during installation. A collapse of the wall would allow the river to rise into housing areas and create damage to existing buildings. A survey program was implemented to observe every movement during installation to ensure that failure did not occur during installation. The design undrained shear strength was 150 kPa for columns installed in perpendicular inclined panels to the existing wall. Columns installed along the wall had design undrained shear strengths of 300 kPa. To achieve 300 kPa the columns were mixed twice with 150 kg/m^3 cement at each mixing. Column strength was validated using pull out resistant tests (PORT). Test results varied between 150 kPa and 500 kPa shear strength in the columns.

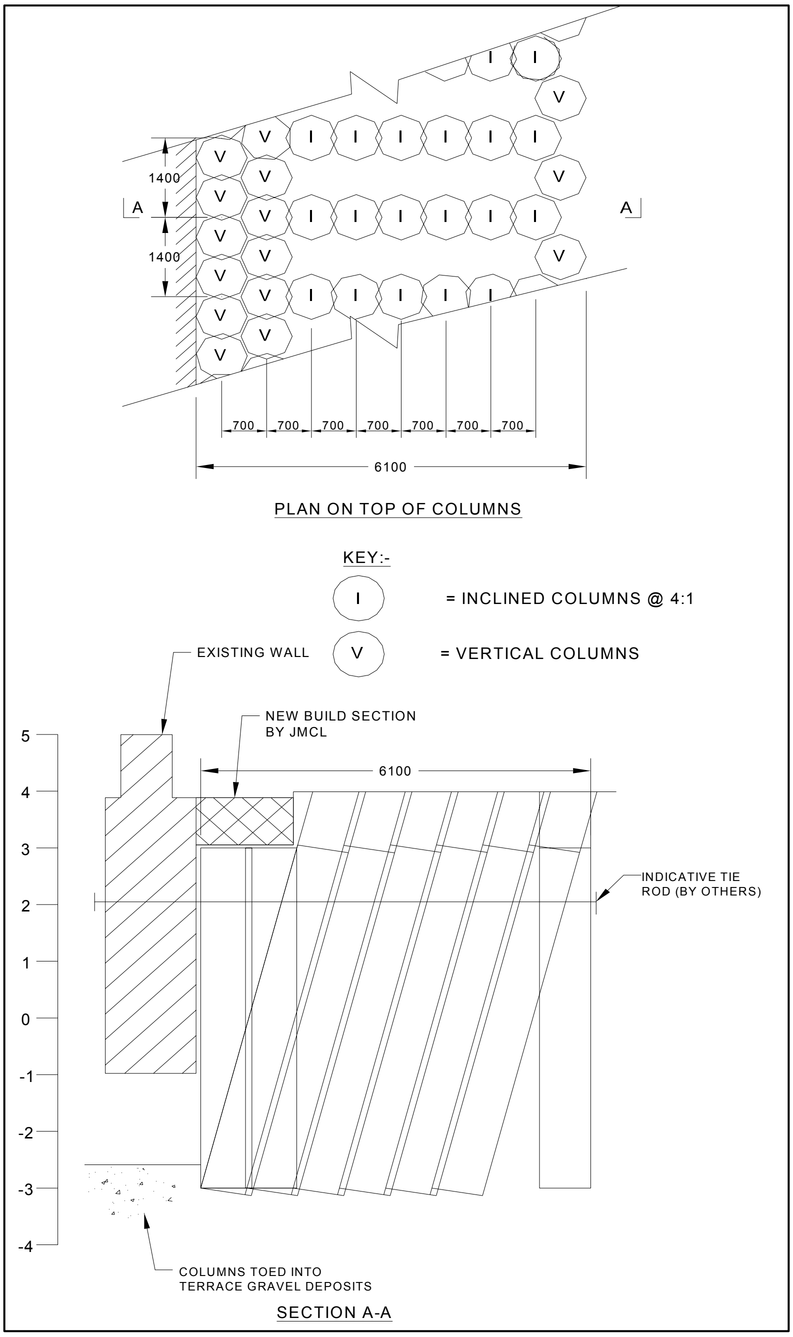

Figure 9: Plan and section drawing for columns installed to support a mass gravity wall at Barking, United Kingdom.

3 CONCLUSION

The development of the LCM method, since it was first used in the seventies, has allowed new and varied applications offering innovative solutions to engineering challenges. The increase in applications has raised interest in using the method outside Scandinavia. Today the LCM system is a well known ground improvement technique worldwide and has successfully been used in Central Europe, United Kingdom, United States, Asia and most recently in Australia. The LCM method forming columns with undrained shear strengths of 100 kPa to 300 kPa has proven to be an economical and technically sound solution in very soft clays worldwide. It is however of great importance to keep in mind that LCM or DDM is a soil improvement system using combined parameters where column and soil interact, and that the method has been developed in Scandinavia for Scandinavian soils. The development of new applications and the introduction into untested soils requires a wide experience of the developed methodology and the achievable parameters and a careful evaluation of and respect for the local soil conditions on every project.

In the future applications using LCM columns will continue to be developed and new areas and countries will adopt the method.

Applications where the LCM method can be considered and extended include stabilising contaminated soils, wider use of high strength columns, for mitigation of vibration from high speed trains or plant and stabilisation of flood protection embankments. Areas where the method could be employed are in all types of soft soils especially in flood deltas and clay deposits of great depth.

As the DDM method is developing worldwide new requirements regarding design QA/QC control and performance will be a major task for the LCM method in the future to support the design and development of applications.

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