MDM combines the advantages of Dry and Wet Mixing

Eriksson, H.
Hercules Grundläggning AB, SE-170 80 Solna, Sweden
hakan.eriksson@hercules.se

Gunther, J.
LCTechnology, 1247 Lincoln Bl #140, Santa Monica, CA 90401, USA
johan@lctechnology.us

Ruin, M.
Hercules Grundläggning AB, SE-170 80 Solna, Sweden
magnus.ruin@hercules.se

ABSTRACT: The paper presents the MDM (Modified Dry Method) which incorporates the advantages from wet and dry mixing into one single rig. The method switches seamless from wet to dry during each individual installation. The paper briefly presents some results from three field tests with focus on functionality of installation procedure as well as column quality. Tests were performed in typical soft Scandinavian clay and dry stiff sand. Finally, some results from a foundation of a parking garage on MDM columns are presented.

1 SOME DRAWBACKS AND ADVANTAGES OF DRY MIXING

Nordic Dry Mixing has its origin in the improvement of very soft clays performed with small lightweight rigs with a torque capacity of approximately 5 to 10 kNm. The evolution towards longer and stiffer columns with increased binder quantities as well as widened applications has required development of the equipment. The machines have become heavier to sustain the twenty to twenty-five meter long leaders and rotary tables with torque in the order of 40 kNm. The available pressure of the compressed air has also increased from 0.2 to 1.0 MPa (Bredenberg, 1999).

Computer controlled installation process is the prevailing system for many contractors performing dry mixing. The binder quantity, penetration and withdrawal speed, rotation speed, leader inclination and air pressure are monitored (Hansson *et al*, 2003). The computer control focuses on mixing energy and binder quantities. However, the accuracy of the scales is often limited to ±2 kg. For typical dry mixing projects, the binder quantity is approximately 80 kg/m^3 to 100 kg/m^3 and the accepted deviations 10 to 20%. This results in acceptance criteria in the same order as the system resolution.

For long columns, the required air pressure is often as high as 0.6 to 1.0 MPa to be able to exceed the back pressure. The high pressure and large air volumes (8 to 10 m^3/min.) introduced into the soil requires extensive consolidation even if part of the air dissipates during the installation. During withdrawal, especially through a competent dry crust, a crater is often created due to insufficient disaggregation of the crust and blockage of the air (Figure 5).

Some advantages and drawbacks for dry mixing are summarized below:

- Advantages
  - Easy to mobilize
  - Low ground pressure under crawlers
  - High installation capacity
  - Cost-effective
  - No or low spoil quantities
  - Low noise and vibration levels
  - No premixing required
  - Can be performed in peat, gyttja, very soft clay as well as silt and sand
- Drawbacks
  - Limited to very soft and soft soils
  - Introduces large quantities of air during installation
  - Often requires surcharge to consolidate the composite soil
  - Causes heave and soil displacement during installation
  - Lack of accurate quality control methods

2 THE PRINCIPLES OF THE MDM SYSTEM

During installation, the dry binder is fed pneumatically. At the same time, water is added through separate injection ports on the mixing tool. The addition of water facilitates penetration of stiff soils, fluidises low plastic clays as well as ensures the complete hydration of the added binder (Gunther *et al* 2004). During upstroke, the same process as during penetration can be repeated; alternatively, only binder is added as long as sufficient premixing and binder activation has been performed. The mixing energy, water and binder quantities can be varied within three programmed zones during each stroke. The principles of the system are shown in Figure 1.

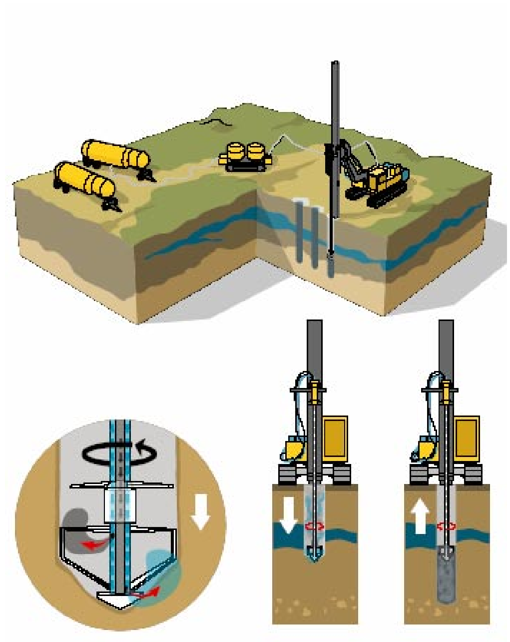

Figure 1 Site logistics and principles of the MDM process.

The equipment consists of a specially equipped mixing tool and appropriate valves for water, in addition to a pump and control means for the water to be injected. Water and binder are fed through individual conduits to the mixing tool and are injected into the soil through separate nozzles to prevent clogging (Figures 2 and 3).

Figure 2 Example of mixing tool used at the Gamletull jobsite in Halmstad. Binder outlet and valves for water are shown.

The rigs are standard dry mixing units with a separate carrier and installer. In order to execute the MDM process, the rigs are equipped with a separate water tank, water pump and flow cell. As for the conventional dry mixing, also the water quantity and pressure are governed by the PLC and monitored by the cabin computer.

Figure 3 Peripheral conduits for water and central part of hollow stem for binder transport.

Compared to dry mixing, the MDM experiences the following advantages:

- Penetration of stiff to firm soils
- Immediate activation and hydration of large quantities of binder
- Fluidization and disaggregation of plastic soils
- Higher homogeneity
- Stabilization of dry soils

Due to the flexibility of the system, the number of suitable applications increases. Direct foundation on high-strength columns as well as installation of cut-off walls is easily performed as a consequence of the modified system. If required, the columns can be reinforced with e.g. steel pipes.

3 FUNCTIONALITY FIELD TESTS

The following field tests are only briefly described. Instead reference is made to the paper by Gunther *et al* (2004).

3.1 Very soft clay at Bro

An initial field test was conducted on a typical soft clay site west of Stockholm. The subsoil comprised three meter competent dry crust overlaying very soft clay on moraine.
At this stage, the introduction of binder was only possible during withdrawal of the mixing tool.

The primary aim was to adjust and modify the installation process as well as compare conventional dry mixing with the MDM regarding homogeneity.

For both column types, a binder quantity of 100 and 300 kg/m^3 was used.

Core sampling was performed on one column of each method whereupon visual inspection was conducted to gain information on the quality of the columns (Figure 4). Core sampling was performed in columns installed with 300 kg/m^3 binder. In the columns with high binder content, it was evident that the binder was activated to a higher degree when water was added during the installation process, even if the natural water content was sufficient to hydrate the binder.

Another observation during this initial field test was the possibility to perform MDM columns all the way up to the ground surface, through the competent dry crust. It is a well-known phenomenon that dry mixing can not disaggregate the dry, stiff clay sufficiently, often resulting in craters during the withdrawal through the dry crust (Figures 5 and 6).

Figure 4 Core samples from Dry Mix- (left) and MDM-columns (right). Both columns were installed with 300 kg/m^3 cement.

Figure 5 Crater experienced during installation of Dry Mix column.

Figure 6 MDM column performed through the dry crust. Excavation has been conducted for the upper 0.5 meters.

3.2 Dry, stiff sand at Tullinge

The Tullinge site is situated within a sand quarry of fluvial deposits with the ground water level located at great depth. The soil profile, according to Swedish Weight Sounding, consisted of medium dense to dense, slightly silty sand. The sand was semi-dry and had occasional horizontal layers of fine silt. Figure 7 shows the results of the Swedish Weight Sounding (Smoltczyk, 2002). Based on empirical correlations (Bergdahl, 1984), the weight sounding results corresponds to (CPT) q_c-values in the order of 15 to 25 MPa.

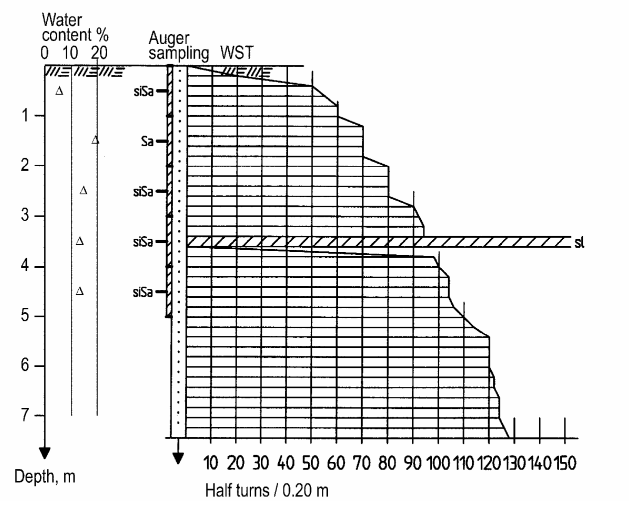

Figure 7 Swedish weight sounding test at Tullinge (lower plateau).

Eighteen, 10 m long columns were installed with 100, 300 and 450 kg/m^3 cement (CEM II/A-L).

The introduction of binder was only performed during the withdrawal stroke.

After 4 months of curing, some of the columns were extracted at five meters depth for further visual inspection (Figure 8). Single barrel core sampling was performed in 4 columns. The unconfined compressive strength varied from 1.5 to more than 11 MPa (Figures 9 and 10). The variation is quite normal for deep mixing and due to many factors such as:

- Varying aggregates
- Varying mixing energy
- Varying binder quantity
- Varying water/cement ratio
- Single or double stroke process

Figure 8 Columns installed with 450 kg/m^3 cement in semi-dry sand.

Figure 9 Core sampling performed in MDM-columns.

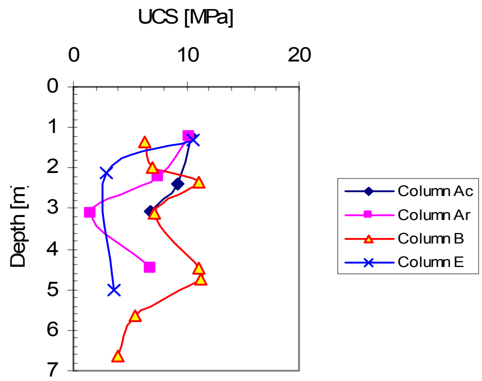

Figure 10 Unconfined compressive strength achieved on core samples at the Tullinge test site.

3.3 Summary of findings

The following main conclusions were drawn during the functionality field tests:

- Columns can be performed in plastic, very stiff clay
- Columns can be performed in very dense and semi-dry sand
- The single stroke process is insufficient when homogeneity is important
- Addition of water improves the column homogeneity

4 COMPARATIVE TEST EMBANKMENT IN VERY SOFT CLAY WITH HIGH SENSITIVITY

Two test embankments were built at a soft clay site on the west coast of Sweden, close to the town of Uddevalla (Figure 11).

One embankment was performed with MDM and one with traditional dry mixing.

Figure 11 Construction of 3 m high test embankments.

4.1 Aim and scope of the field test

The purpose of the field test was to compare the behaviour of the two test embankments. The following details were investigated during and after construction of the embankments:

- Functional behaviour of embankment
  - Settlement
  - Generated pore pressure
  - Stress distribution
- Column quality
  - Visual inspection
  - Unconfined compressive test
  - Chemical analysis (not presented here)

The geometry of both embankments was approximately 225 m^2 (15 by 15 m) and the height was 3 m. The fill comprised sandy gravel from a nearby borrow-pit.

The MDM-columns were installed with a spacing of 2.2 m and a length varying from 8 to 12 m. All columns had binder content (100% CEM II/A-L) of 450 kg/m^3. A load transfer platform with three Tensar geogrids was installed above the columns (Figure 12).

The dry mix columns had a spacing of 1.2 m and the length varied from 12 to 14 m. Binder comprised a 50/50 blend of unslaked lime and cement (CEM II/A-L). The binder content was 90 kg/m^3.

All columns had a diameter of 0.6 m and the binder was only introduced during withdrawal of the mixing tool.

In the central part of the MDM-embankment, two pore pressure gauges were installed. Above and between two columns, four pressure gauges were mounted with purpose to compare the generated stresses and thereby validating the design model (Figure 13). A total of six settlement gauges registered the settlement above and between columns.

The dry mix embankment had a similar instrumentation except for the pressure gauges which could not be installed due to practical reasons.

After installation, the columns were cured for approximately one month before construction of the embankment commenced.

Figure 12 Installation of load transfer platform.

Figure 13 Pressure cells installed above column, on a cushion of sand (Soil Instruments Ltd).

Monitoring of the embankments was performed for approximately three months.

4.2 Subsoil investigations

The following soil investigations were performed on the virgin soil:

- Static penetration test
- Undisturbed sampling with evaluation of
  - Shear strength
  - Oedometer modulus
  - Consistency limits
  - Sensitivity

The soundings and laboratory analyses showed that the dry crust was approximately 3 m thick with shear strength in the order of 200 to 300 kPa. Shear strength in the normally consolidated clay was rather constant. The fall-cone test assessed the shear strength to approximately 20 kPa (Figure 14). The sensitivity of the clay was high throughout the whole profile, increasing to become quick clay at greater depth.

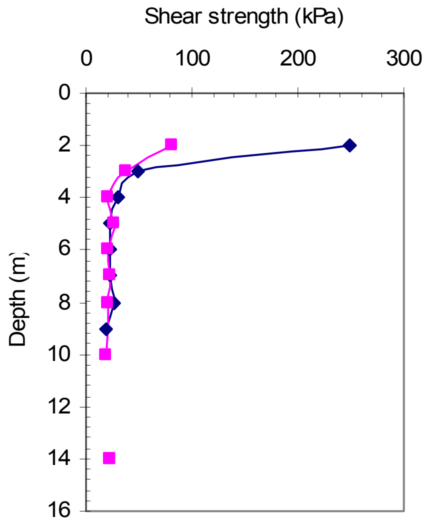

Figure 14 Undrained shear strength evaluated from the Swedish fall-cone test on undisturbed samples.

The water content was in the same level as the liquid limit or higher. Liquidity index varied from 0.2 in the dry crust increasing to almost 3 at greater depth (Figure 15).

Due to the high sensitivity (and high liquidity index), the test site was very suitable to conventional dry mixing.

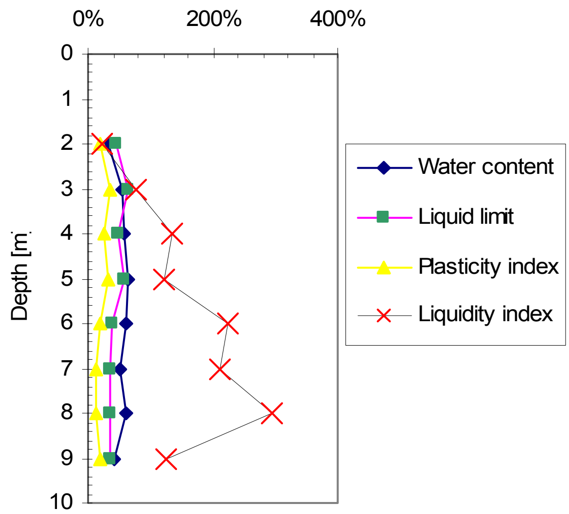

Figure 15 Water content and consistency limits for the very soft clay at Uddevalla.

4.3 Investigation of column quality

Column quality was checked by performing unconfined compression tests on core samples (Figures 16 and 17). The sampling was performed with a 72 mm double, split tube barrel (column D5 in Figure 17) as well as a 45 mm single barrel (column D4 in Figure 17).

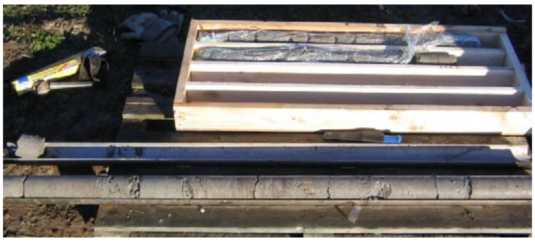

Figure 16 Core samples taken in the MDM-columns.

The results varies to a great extent due to the single-stroke installation procedure, influence by the sampling method and to some extent the varying soil conditions. However, it is confusing that the samples taken by the single barrel generally gives higher column strength than the double barrel.

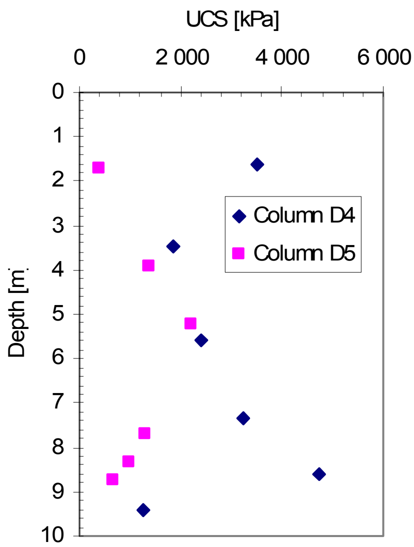

Figure 17 Unconfined compressive strength versus depth for core samples taken by the single (D4) and double (D5) barrel core sampler.

A number of reasons for the variation can be found, including:

- Single-stroke installation procedure
- No computer control of the injection of water
- Variation of aggregate in the soil

Most likely, the single stroke procedure, where the binder is introduced during withdrawal, creates thin zones with lack of binder.

The secant Young's modulus is often assessed as a factor times the unconfined compressive strength. This empirical factor normally lies between 50 and 100 and for the actual core samples the same factor falls between 70 and 200 (Figure 18). The failure strain varied between 0.8 and 1.2%.

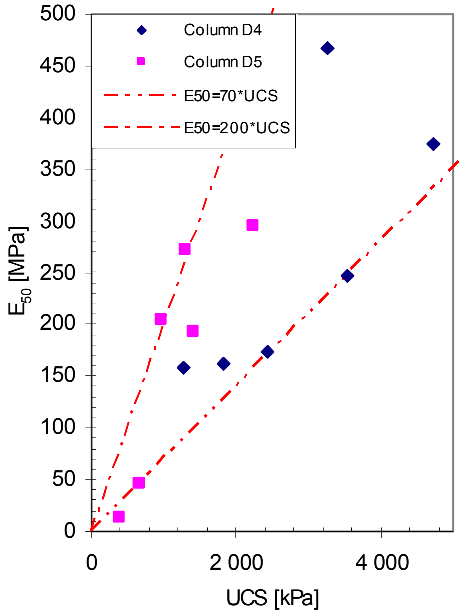

Figure 18 Young's modulus as a function of unconfined compressive strength.

4.4 Evaluation of embankment behaviour

The MDM-embankment was built to full design height during one week. After two months of consolidation, another 1.5 m was added.

The primary consolidation was completed after approximately one week (Figures 19 and 20). When the additional surcharge was added after 2 months of consolidation, the primary consolidation for that step was equally fast. However, some secondary consolidation was ongoing when the monitoring had to be aborted due to practical reasons (the test area, located on a farm land, was only rented for three months).

The measured stresses above and between columns diverged from the theoretical, using the Young's modulus evaluated from the unconfined compression tests and virgin soil stiffness according to the CRS oedometer tests. However, the stress cells were installed on a cushion of 0.3 m of sandy gravel and the three metre thick dry crust was not taken into account. At a post-construction 3D-Plaxis analysis, the accurate soil and column parameters were accounted for and resulted in roughly the same stresses as in Figure 21.

Primary consolidation for the dry mix embankment continued for a much longer time. Even after three months, the excess pore pressure was slightly higher than the initial steady state pore pressure.

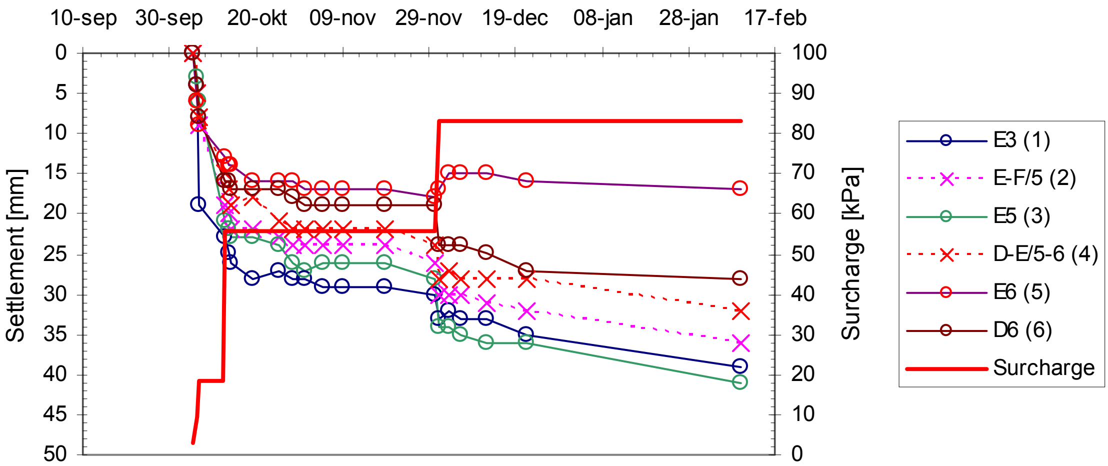

Figure 19 Experienced settlement of MDM-embankment. Circular points are settlement gauges above columns and crosses are gauges located between the columns.

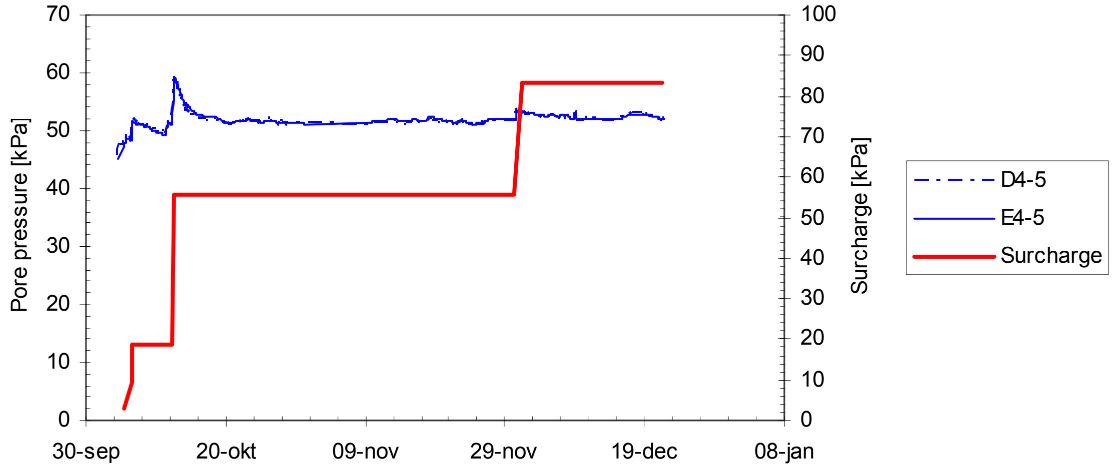

Figure 20 Pore pressure measured between the columns at the centre of the embankment. Gauges were installed to approximately 5.5 m depth.

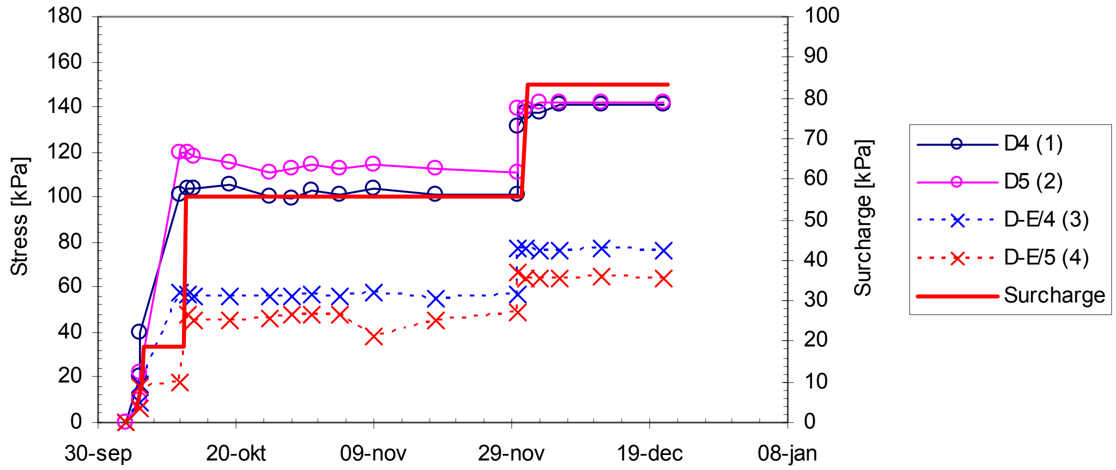

Figure 21 Stress measured with pressure cells. Circular points are pressure gauges above columns and crosses are gauges located between the columns.

5 COMPETITIVE FIELD TEST IN HALMSTAD

At a site in the centre of Halmstad, on the west coast of Sweden, the local government awarded Hercules Grundläggning the contract to perform the foundation of a parking garage. Due to settlement-sensitive buildings in the surroundings, the recommended pile type was bored or auger pile types. The contract was won with CFA-piles as the solution. The client accepted that pre-tests were performed with MDM-columns with the purpose to evaluate and compare achieved quality and costs with the recommended CFA-solution (Figure 22).

The test was split into three different steps:

- Development of installation procedures
- Visual inspection of MDM-columns
- Static load tests on columns installed in blocks

The soil at the site was layered and comprised sand overlaying silty clay on top of another layer of sand, very soft clay and sandy silt. The ground water was located approximately 1.5 m below ground level.

After the initial modification of the installation procedure and visual inspection, two columns were installed to a depth of 7 m followed by the insertion of a 63.5 mm central GEWI-bar. After one week, the columns were load-tested followed by extraction of the whole columns (Figure 23). Based on results from static tension tests (Figure 24) and extraction of the columns, evaluation of the shaft resistance was performed and correlated with the bearing capacity achieved from the model proposed by Eslami and Fellenius (1997).

Figure 22 View of the construction site at Gamletull, in Halmstad.

Figure 23 Extraction of whole columns.

The 7 m long extracted columns were laid down horizontally on the ground for inspection. The first column broke when it was laid down due to moment of its own weight. Based on the measured length (projected horizontal length when the column failed), diameter and weight of the column, the tensile strength was evaluated to 1100 kPa. According to Terashi *et al* (1980), the tensile strength is in the order of 10% to 20% of the unconfined compressive strength. For the actual column, the average compressive strength then becomes 7.3 MPa which is in the same order as the performed unconfined compressive tests (Figure 30).

A specially equipped wire saw was used to cut slices out of the column (Figure 25).

Roughly three weeks after installation of two blocks comprising 9 overlapping columns, static load tests were performed. The columns were installed to 12 and 16 m depth below cut-off level. The design loads for the blocks were 2100 kN and the intention was to load the blocks with 3000 kN. Block number one (Figure 26) achieved a permanent settlement of 4 mm at the design load. The requirement set up by the client was an accepted settlement of 40 mm with a maximum differential settlement of 1:800. For block number two (Figure 27), one of the reaction anchors failed at a load of approximately 2000 kN so the test had to be aborted. However, the behaviour was perfectly elastic and no permanent settlement was achieved, nor on top of the slab, neither at six metres depth (monitored by tell-tales).

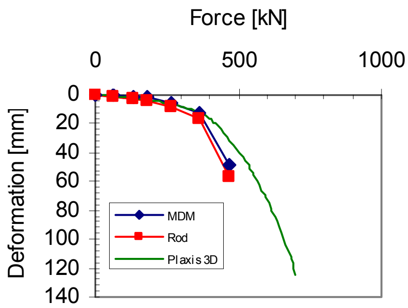

Figure 24 Tensile load test on single, 7 m long, MDM-column performed one week after installation.

Figure 25 Cutting of extracted columns using a wire saw. The GEWI-bar is visual in the middle.

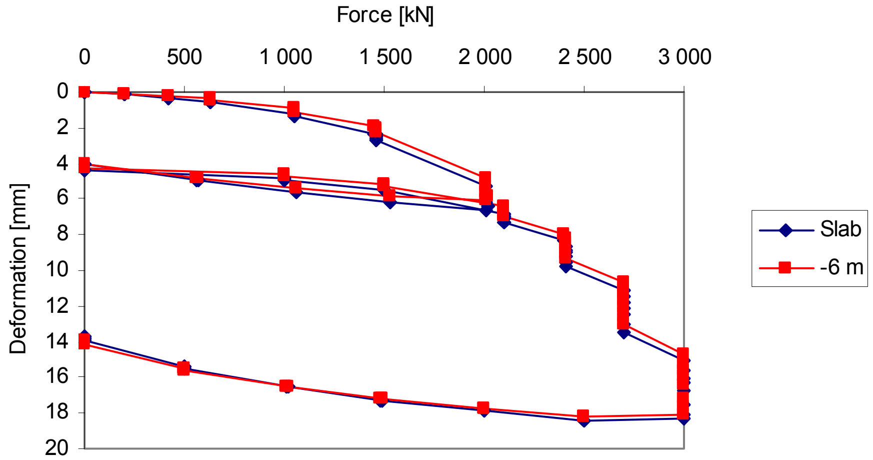

Figure 26 Static load test performed on a block of 9 MDM-columns according to the maintained load test procedure. The columns were 12 m long and installed overlapping by 100 mm.

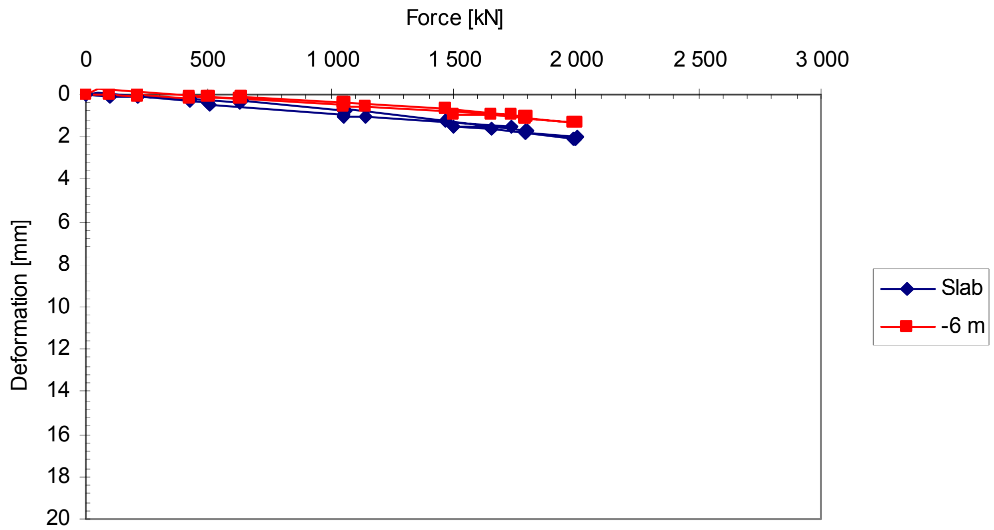

Figure 27 Static load test performed on a block of 9 MDM-columns according to the maintained load test procedure. The columns were 16 m long and installed overlapping by 100 mm. During load test, one of the tension anchors failed and the load test had to be aborted.

After a revised design based on the performed field tests, it was decided to change from CFA piles to the MDM concept. The main advantages for this specific project were:

- Lower cost
- Reduced installation time

The columns were performed without reinforcement. The horizontal forces were taken care of by direct shear in the columns and contact stress in the soil.

Based on anticipated compressive strength of 3 MPa, the design strength was set to 850 kPa. This resulted in installation of approximately 500 columns with lengths varying from 14 to 16 m below cut-off level.

Three out of 48 slabs were installed close to an existing building. The horizontal movement and uplift was measured to 5 mm which was within the acceptable limits. Complete installation of all columns took approximately 3 weeks.

Quality control of the columns was performed by taking core samples in 5 columns followed by unconfined compression tests performed at the Swedish Geotechnical Institute (Figure 30). The variation of column strength follows quite well the variation of the virgin soil. Between nine and twelve metres depth, there was a soft clay layer present. Above and below this layer, the soil was dominated by silty sand and sandy silt with some clay inclusions.

All columns were installed overlapping, forming blocks comprising 4 to 32 columns (Figure 28).

Figure 28 Block of columns excavated down to cut-off level directly after installation.

Figure 29 Concrete slab casted directly on the block of 9 columns.

After two days of curing, the slabs were cast directly on top of the columns without any further preparation (Figure 29).

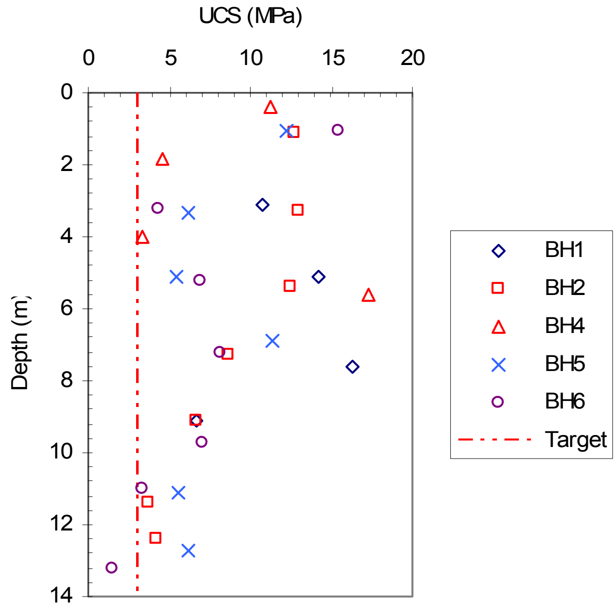

Figure 30 Results from unconfined compression tests performed on cores from 5 different columns.

6 CONCLUSIONS

Based on the field tests and the foundation of the parking garage, the following conclusions are drawn regarding the MDM system:

- The spoil is limited to 0.05 – 0.1 m^3 per column, independent of column length
- Limited horizontal and vertical displacements were experienced during column installation in layered sandy, silty and clayey soils close to the existing building
- Columns can be installed in very dense, dry sand
- Columns can be created in very stiff dry crust
- Despite the assumed low permeability of the columns, the consolidation in soft clay requires shorter time then conventional dry mix columns
- The overall time for completion as well as the project cost is reduced
- The type of applications is widened due to the possibility to conduct dry mixing as well as MDM with the same equipment, even for the same column
- Reinforcement can easily be installed in the liquefied column directly after installation
- Unconfined compressive strength in the order of 3 and 10 MPa can be achieved in soft clay and sand respectively.
- Columns in combination with load transfer platforms creates high quality, cost-effective solutions

7 ACKNOWLEDGEMENTS

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