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Design and Construction of Granular Soil Columns for Ground Improvement of Very Soft Soils for Road Embankments

Stavros A. Savidis
Berlin Institute of Technology, Germany

Frank Rackwitz
Berlin Institute of Technology, Germany

Maik Schüßler
Brandenburg Highway Department, Hoppegarten, Germany

DESIGN AND CONSTRUCTION OF GRANULAR SOIL COLUMNS FOR GROUND IMPROVEMENT OF VERY SOFT SOILS FOR ROAD EMBANKMENTS

Stavros A. Savidis
Professor Dr.-Ing.
Chair of Geotechnical Engineering
Berlin Institute of Technology
Germany

Frank Rackwitz
Dr.-Ing., Research Associate
Chair of Geotechnical Engineering
Berlin Institute of Technology
Germany

Maik Schüßler
Dipl.-Ing.
Brandenburg Highway Department
Hoppegarten
Germany

ABSTRACT

The first presented case history is the construction of a new federal road south of Berlin, Germany. An embankment has been designed to cross a region of very soft peat soil with underlying organic silt, sand and boulder clay, with a total length of about 140 m. Ground improvement using sand columns with a diameter of 0.6 m and a distance of 1.5 m were designed and applied to all regions with more than 2.5 m thickness of the organic soil layer. Geogrids were used in addition to the vertical sand columns to take into account the action of horizontal forces beneath the embankment. The measured settlements as well as the tensile strains in the geogrids show the significant creep behaviour of organic soils over very long periods of time.

The second case history is the renewal and enlargement of a federal expressway resting on very soft organic soils. Extensive laboratory tests as well as a large scale model test in a geotechnical testing pit using in situ excavated organic silt have been done to investigate the soil-column interaction behaviour in more detail. The data confirm that the long term deformations of the organic soils are mainly influenced by the creep behaviour of these soils.

INTRODUCTION

Infrastructure projects, such as roads and railway lines, have sometimes to be planned through regions with very soft underground conditions. Soil improvement techniques are required in such cases if soil replacement is not a possible that means cost-intensive solution. A number of different improvement methods are available and known, such as deep mixing methods using lime or cement and mechanical stabilization methods (Bergado et al., 1994). Among these methods the use of granular soil columns for ground improvement is very cost effective if granular soil is sufficiently available nearby the construction site. The drainage of the soft soils is accomplished by the granular soil columns itself. Another advantage is the fact that these columns also increase the stiffness and the strength of the soft soils.

The behaviour of the soft organic soils have to be taken into account and should be carefully investigated to arrive at a suitable design of the ground improvement. There is less literature about organic soil behaviour compared to other typical sediments due to the wide variability of the composition and occurrence of that kind of soils. The compression and consolidation behaviour and the creep effects are of special interest when investigating organic soils.

GEOLOGY AND PHYSICAL PROPERTIES OF SOFT ORGANIC SOILS IN THE AREA OF BERLIN AND BRANDENBURG

Geological Situation

The local area of Berlin and Brandenburg is situated in the northern lowlands of Germany. More than 10 % of the area of Berlin-Brandenburg are moor regions with very soft soils.

The geology of the area Berlin-Brandenburg is characterized by saturated deposits of the quaternary stratum. Three different glacial periods can be identified there: Elster, Saale and Weichsel ice ages. The glacial sediments of these ice ages and the interglacial warm periods are highly irregular in their horizontal and vertical distributions and also vary widely in their composition. They consist of tills, sands, gravels, boulder clays and organic soils. The very soft organic soils deposited mainly in the past ice ages era, the Holocene, and are located in narrow valleys with organic silt at the bottom and peat soil on the top. The degree of decomposition of these organic soils varies with the depth of the strata. Ground water is usually found in the sand layer approx. 3 to 5 m below the ground surface. The ground water table is confined underneath the organic soil layer. It can reach the ground surface depending on the seasons.

Physical Properties of the Soft Organic Soils

The particle composition of the soft organic soils is pictured in Fig. 1, taken from Scanning Electron Microscope investigations of a soil sample. Organic parts can easily be identified in this picture.

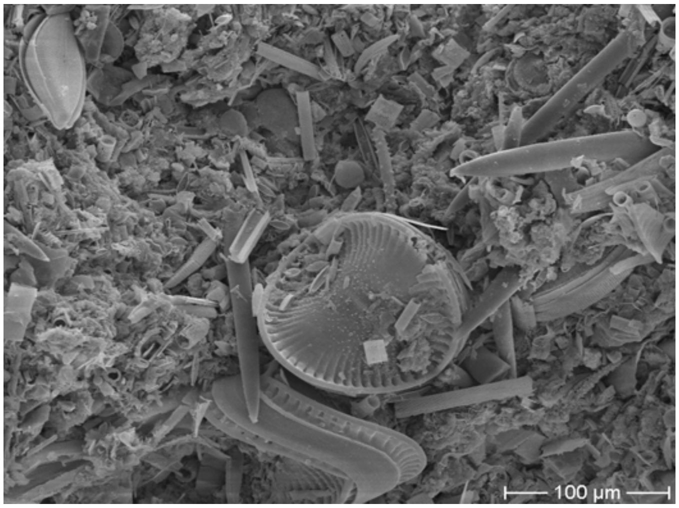


Fig. 1: Microscopic composition of organic soils. Picture taken from Scanning Electron Microscope (SEM) investigation.

The organic content and the solid density have been determined for more than 300 soil samples taken from different peat and organic silt and clay strata. Based on the evaluation of these laboratory analyses a correlation between the solid density and the organic content of soft soils in the local area of Berlin was found (Fig. 2).

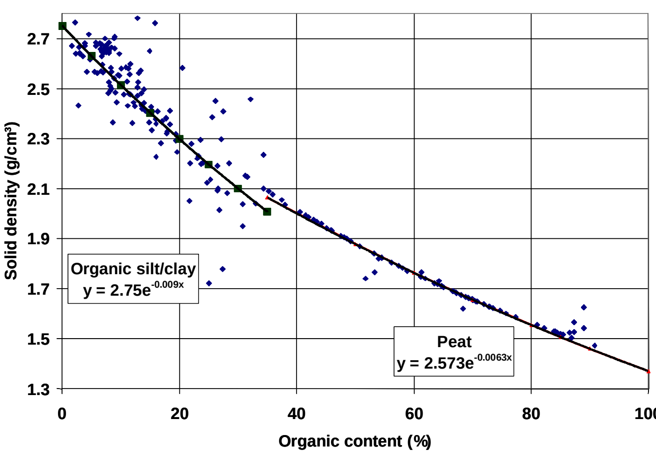


Fig. 2: Correlation between solid density and organic content for soils in the area of Berlin, Germany

Figure 2 reflects the strong interrelation between the organic content and the solid density for these soft soils and gives the possibility to classify organic soil samples. Especially the solid density of the peat material can obtain very low values due to the high organic content of that kind of soils.

FEDERAL HIGHWAY B96 SOUTH OF BERLIN

General Project Information and Subsoil Conditions

A new federal road south of Berlin, Germany, was to built in association with the planning and construction of the new Airport Berlin-Brandenburg International (BBI). The new road is crossing through a region of very soft peat soil with underlying organic silt, sand and boulder clay on a total length of about 140 m (Fig. 3).

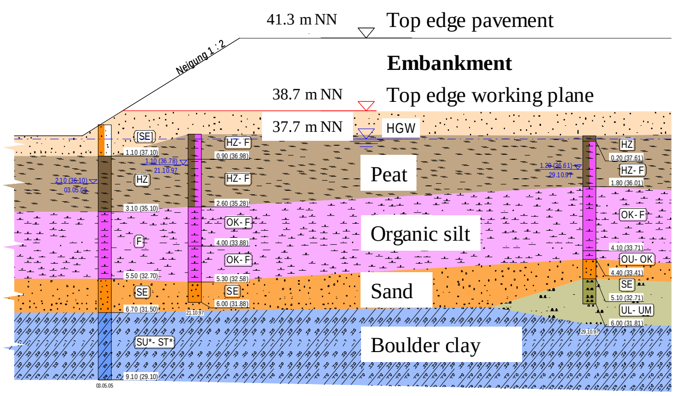


Fig. 3: Federal Highway B96 - Subsoil conditions and typical cross section with the road embankment

The in situ water content of the peat material from the site investigation was up to 430 % and from laboratory tests an undrained cohesion of less than about 8 kPa for the organic silt was obtained. An embankment resting on improved ground has been therefore designed to cross this area of soft soils.

Design of the Ground Improvement Using Granular Soil Columns

Sand columns with a diameter of 0.6 m and a distance of 1.5 m were designed to be applied in all regions with more than 2.5 m thickness of the organic soil layer (Fig. 4).

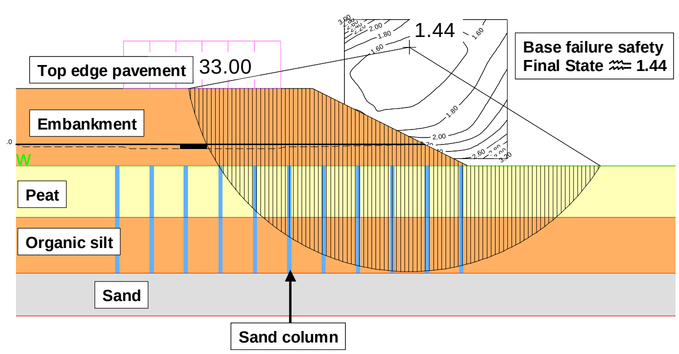


Fig. 4: Slope stability analysis for the final design stage of the road embankment

Geogrids were used on the base of the embankment in addition to the vertical sand columns to take into account the action of horizontal forces beneath the embankment. Figure 4 illustrates the results from slope stability analyses according to German code DIN 4084 (1981) for the final design state of the embankment. A global safety factor of 1.44 resulted from these analyses (Savidis et al., 2006, Schüßler et al., 2006).

Finite element calculations using the commercial program PLAXIS V7 (2006) were performed in addition to the classical limit stability analyses.

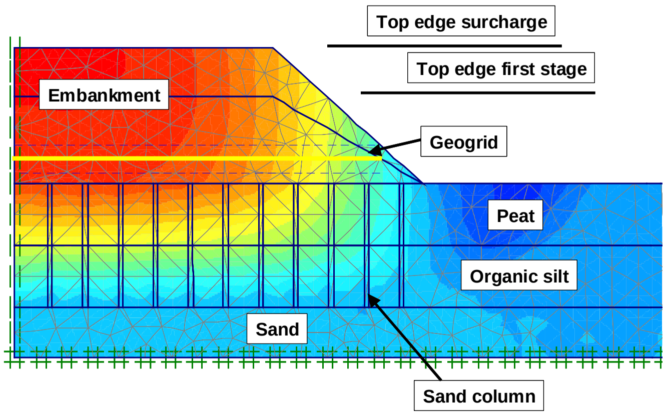


Fig. 5: Finite element model with contour plot of vertical displacements in the stage of full surcharge loading

A 2D finite element model with plane strain condition was generated. The organic soils were modelled using the Soft-Soil model (Plaxis, 2006) and the remaining elements using the Mohr-Coulomb model respectively. The loading stages were modelled as they were constructed, i.e. in two stages. The second construction stage of the embankment provided a surcharge load for the reduction of consolidation time.

Figure 5 presents the finite element model in the final stage with a contour plot of vertical displacements. A maximum settlement of 28 cm of the top edge in the first stage as well as 58 cm in the surcharge stage of the embankment construction were calculated. The additional analysis using a model without sand columns resulted in 107 cm settlement with surcharge loading. Based on these calculations a reduction of 45 % of the improved soil compared to the natural conditions could be achieved.

Construction of Ground Improvement

The granular soil columns were constructed using sand from nearby locations. First a closed-ended steel pipe (Fig. 6) was vibratory driven into the ground, displacing the surrounding soft soils. In the second step the sand was filled into the pipe. The initially closed bottom end of the pipe (Fig. 6) is released when the pipe moves upward in the following construction step. Finally the pipe was pulled out with stepwise cyclic movement up and down. More than 2,300 sand columns were installed on an area of approx. 5,500 square meters.

Fig. 6: In situ installation of granular soil columns

Figure 7 illustrates the embankment construction sequence starting from the working plane and finishing with the surcharge loading. The surcharge load was removed at the end of the required consolidation time of the subsoils. Three of the measuring sections along the embankment are also shown in Fig. 7.

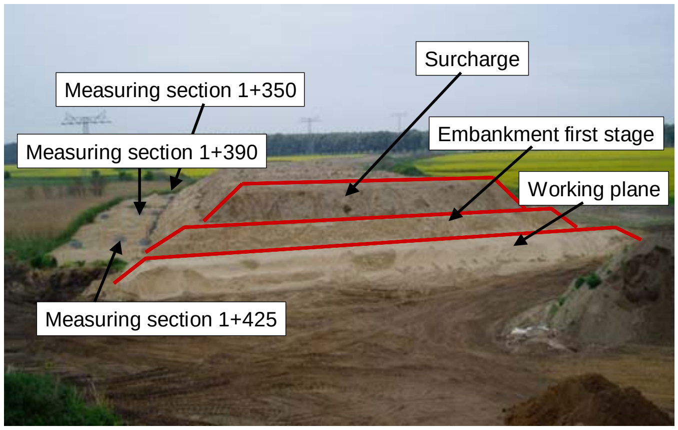


Fig. 7: In situ situation during the construction process in May 2006

Measurements During the Installation of the Granular Soil Columns

Six vertical inclinometers were installed to measure the horizontal movement of the subsoil during and after the construction of the sand columns. They were placed in a distance between 1.5 and 2.5 m from the outer columns in a cross section. Horizontal soil movements between 8 and 25 cm were measured during the column installation works. Pore pressure transducers were placed about 2 m outside the embankment in the organic silt (transducer U 2 in Fig. 8) and in the peat soil (transducer U 3 in Fig. 8).

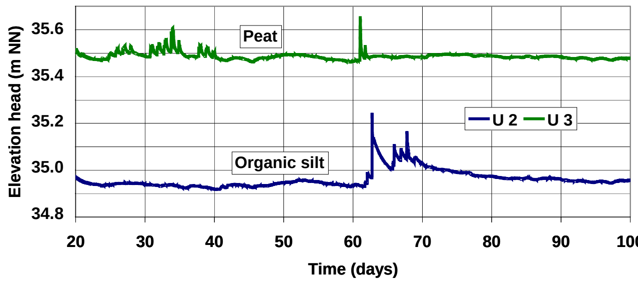


Fig. 8: Pore pressure changes in the soft soils during the sand column installation

Figure 8 represents the results of the measured pore pressure changes. The measured peaks with excess pore pressure of 2 to 3 kPa are due to the close installation of a sand column at that time of measurement. The closest distance between pore pressure transducer and installation pipe was about 2 m. A reduction to approx. 50 % of the excess pore pressure was measured within 1 hour after the peak pore pressure occurrence.

Measurements After the Installation of the Granular Soil Columns

Six additional vertical inclinometers were placed inside the sand columns and six horizontal inclinometers on top of the working plane after the installation works were finished. The maximum settlement of the embankment was measured with 54 cm in measuring section MS 1+350 about 21 month after the placement of the first loading stage (Fig. 9). No significant difference in the measured settlements has been found between horizontal inclinometers above the sand columns and in-between them.

The installed two geogrids on the base of the embankment were equipped with three strain gauges to evaluate the tensile strains in the geogrids during and after the loading process. Figure 10 shows the measured strains over time in the upper and lower geogrid. The two strain gauges which were fixed at the upper geogrid (Geogrid top and Geogrid middle in Fig. 10) exhibit only half of the strain of the lower geogrid (Geogrid bottom in Fig. 10). The maximum measured strain of approx. -0.8 % in Fig. 10 corresponds to a tension force of 28 kN/m for the FORTRAC R 350/50-30 geogrid which was installed as the lower geogrid at the bottom of the embankment.

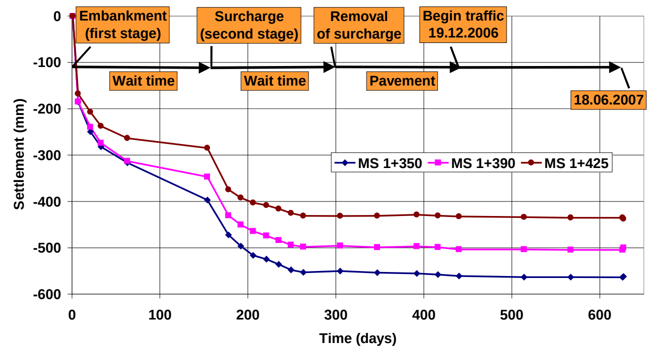


Fig. 9: Measured settlements in the centre line of the embankment starting from the first loading stage

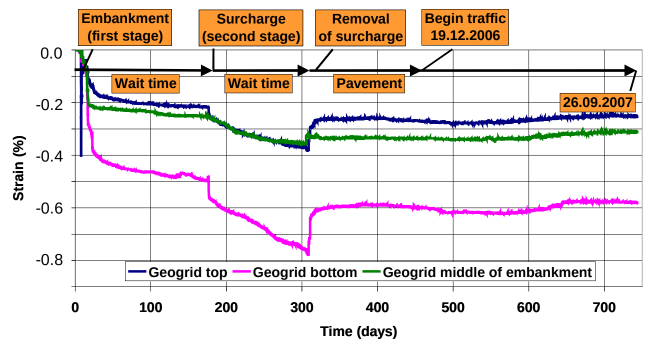


Fig. 10: Measured strains in the geogrids below the embankment starting from the first loading stage

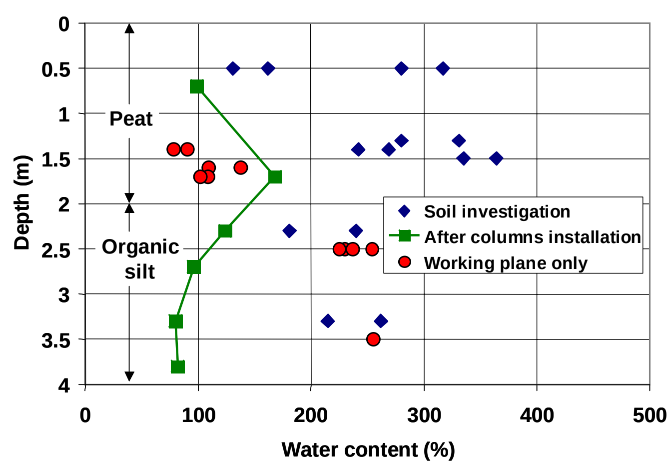


Fig. 11: Water content in the soft soils before and after the ground improvement works

The influence of the construction processes on the in situ water content of the soft soils is displayed in Fig. 11. The water content in the upper peat soil layer decreased considerably already after the construction of the working plane. The drainage of the lower organic silt strata was effective after the installation of the sand columns and therefore the water content decreased compared to the site investigation before the construction works.

Creep Behaviour of the Soft Soils

The measured settlements over time from the horizontal inclinometers below the embankment (Fig. 9) as well as the measured tensile strains from the strain gauges at the geogrids (Fig. 10) show the significant creep behaviour of organic soft soils over long periods of time.

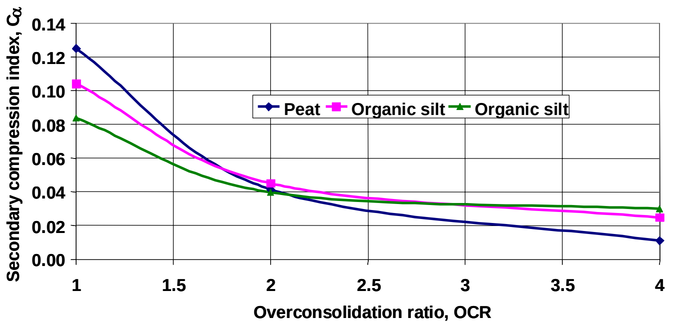


Fig. 12: Effect of OCR on the creep behaviour of the soft soils derived from oedometer tests

Laboratory tests were performed to investigate the creep behaviour of the organic soils in more detail. Figure 12 displays the results from oedometer tests with samples taken from peat and organic silt. The overconsolidation ratio OCR influences the index of secondary compression derived from the oedometer tests. That result has also practical importance which means that a reduction of long term settlements follows from the in situ application of the surcharge loading.

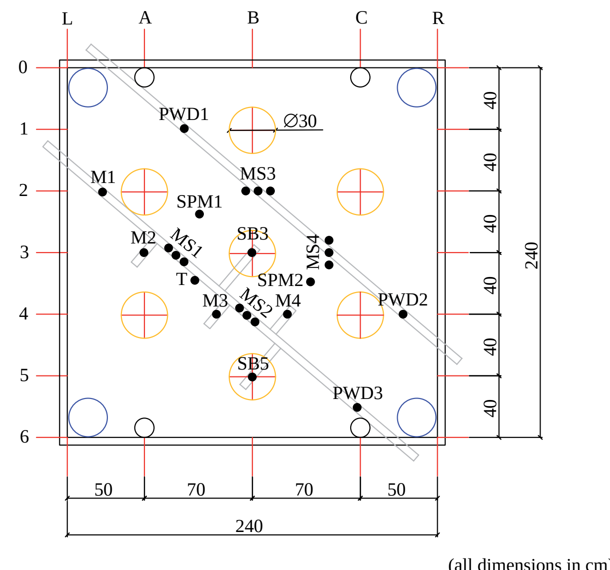
LARGE SCALE MODEL TESTS IN THE GEOTECHNICAL TESTING PIT IN CONJUCTION WITH THE AUTOBAHN A 11 PROJECT

General Information

The second case history is the renewal and enlargement of the federal expressway autobahn A 11, Berlin – Stettin, junction Joachimsthal in the north of Berlin, Germany, which is just under construction. There are extremely soft organic soils with a thickness up to approx. 10 m to be passed by the new freeway junction. The freeway embankment has a total height of 5 m. The use of granular soil columns for ground improvement on an area of about 5,000 m² was planned to construct the new junction. From the site investigation the water content of the organic soils was determined to be up to 1,000 % for the peat and 1,250 % for the organic silt respectively. The organic content was up to 93 % for the peat and 82 % for the organic silt. The undrained shear strength from field vane shear tests and laboratory tests was 2 to 7 kPa only.
In the planning stage extensive laboratory tests as well as a large scale model test in a geotechnical testing pit at the Berlin Institute of Technology (TU Berlin) have been done to investigate the soil-column interaction behaviour in more detail and to check the design principles. The geotechnical testing pit has six boxes which can be used as single boxes or as a whole without separating walls. One single box (width/length/depth = 2.4/2.4/3.7 m) was used for the model test.

Preparation of the Model Tests - Soil Placement and Instrumentation

About 20 m³ of the in situ excavated organic silt was delivered by truck to the laboratory and prepared for the model testing. A 50 cm layer of sand for drainage purposes was placed at the base of the testing pit (Fig. 14). One drainage pipe was positioned in each corner of the pit (Fig. 13). The organic silt was then filled into the pit and manually homogenized. Water was continuously added to reach full saturation. Finally the thickness of the organic silt in the pit achieved about 3 m (Fig. 14).



Sand column
Drainage pipe
Transducer locations with the following labels:

M1 ... 4	Vertical displacement on top of the organic silt surface
MS1, 2	Vertical displacement in three depths (-0.75; -1.50; -2.25 m)
MS3, 4	Total stress and pore water pressure in three depths (-0.75; -1.50; -2.25 m)
PWD1...3	Pore water pressure at -1.50 m below organic silt surface
SPM1, 2	Contact pressure between organic silt surface and surcharge (gravel)
SB3, 5	Contact pressure between top of the sand column and surcharge (gravel)
T	Temperature

Fig. 13: Plan view of the model test arrangement

The instrumentation was installed after the successful placement of the soil in the pit. Four measuring sections MS1 to MS4 were installed (Fig. 13). Six vertical displacement transducer have been placed in three different depths at MS1 and MS2 respectively (Fig. 13, 14). Six combined total stress and pore pressure transducer were installed in three different depths at MS3 and MS4 and additional three pore pressure transducer in a depth of 1.5 m below top surface of the organic silt at different locations (Fig. 13). Two pressure transducer on top of the organic silt surface as well as the sand columns in axes B3 and B5 were installed to measure the contact pressure distribution from surcharge loading (Fig. 13).

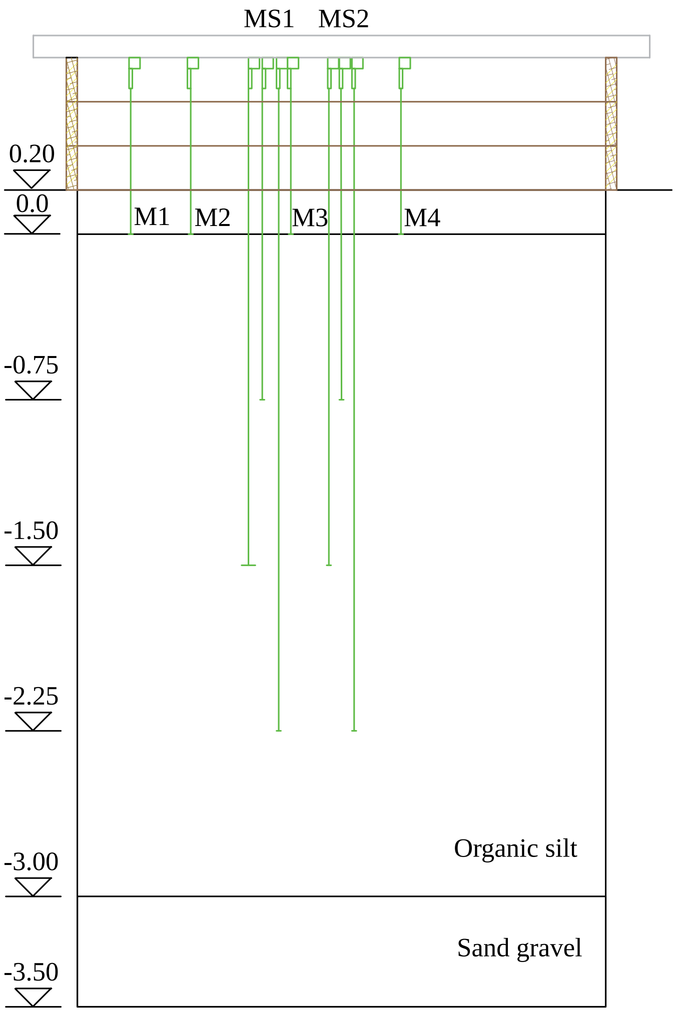


Fig. 14: Sectional view of the displacement transducer locations in the model test arrangement

Four vertical displacement transducer (M1 to M4) were installed on top of the surface of the organic silt (Fig. 13, 14). Finally a temperature sensor were placed inside the organic silt (Fig. 13).

<u>Initial State of the Soil before the Sand Column Installation</u>

The water content before sand column installation was determined at several locations and a mean value of 360 % was obtained. An organic content of 20 % resulted from these investigations.

Oedometer tests were carried out with two samples taken from 0.3 m and 0.8 m below the top edge of the organic silt in axes A0 (cf. Fig. 13) of the pit. The loading, unloading and reloading paths are represented in the void ratio vs. vertical effective stress plane (Fig. 15).

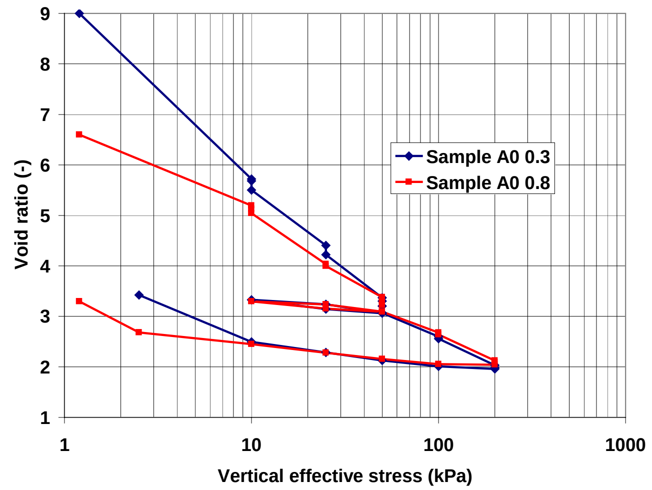


Fig. 15: Behaviour of the organic silt in one dimensional compression tests

The indices of secondary compression vs. compression obtained from these tests are shown in Fig. 16. An increase of the index of secondary compression with increasing compression index can be derived from Fig. 16. The ratio Cα/Cc, which is known as viscosity index (Krieg, 2000), gives a mean value of 0.075 from these tests (Fig. 16).

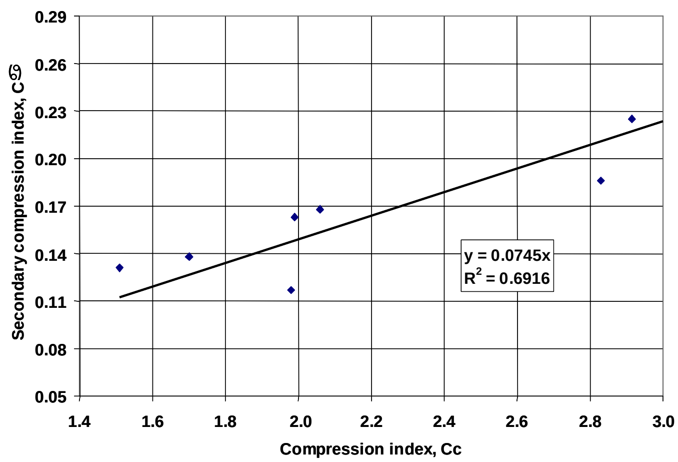


Fig. 16: Correlation of the indices of compression Cc and secondary compression Cα of the organic silt

Field vane shear tests using a vane with height/diameter = 150/75 mm and an electric power system were done to determine the initial undrained shear strength of the soft soil. Tests with a variation of the driving vane velocity were performed to evaluate the dependency of the undrained shear strength on the shear velocity.

Figure 17 shows the results obtained from the vane shear tests with rotation rate of 0.1 and 4.0 °/sec respectively. The tests were performed in different depths from 0.5 m to 2.6 m below top edge of the organic silt.

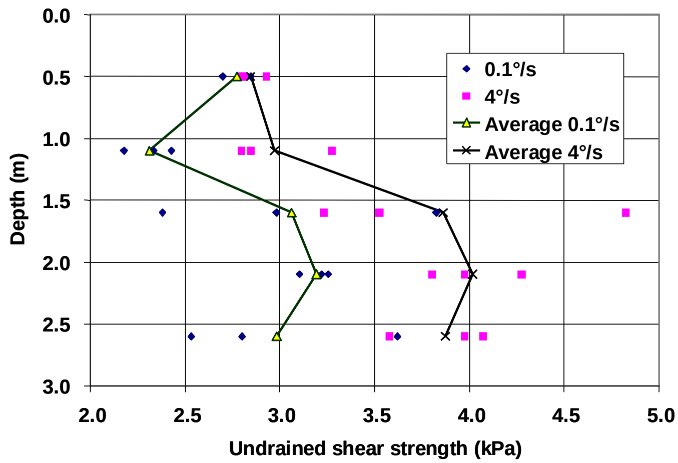


Fig. 17: Results from field vane shear tests before the installation of the sand columns

The mean value of measured vane shear strength is 3.2 kPa. The resulting mean ratio of high to slow speed tests with more than 1 m depth is 1.28. Biscontin and Pestana (1999) give the following relation between undrained shear strength S_u, S_{u0} and respective peripheral velocities v, v_0:

$$\frac{S_u}{S_{u0}} = \left(\frac{v}{v_0}\right)^{\beta} \tag{1}$$

Exponent β in Eq. (1) is a soil dependent material parameter. Based on the own results (Fig. 17) the exponent β was determined to be 0.067 and is close to the viscosity index with 0.075 derived from the oedometer tests mentioned above (Fig. 16).

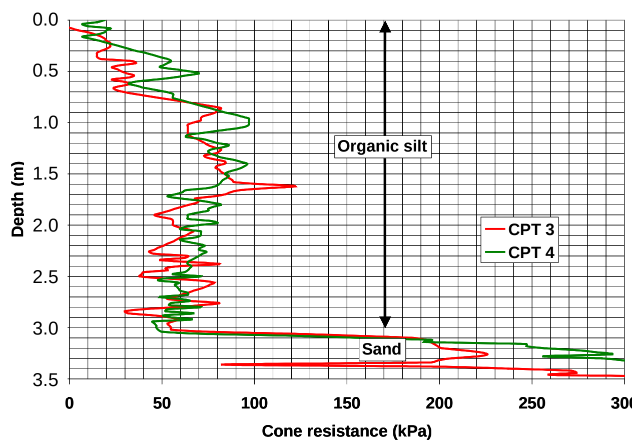


Fig. 18: Results from CPT before the installation of the sand columns

Figure 18 represents the results from Cone Penetration Tests (CPT) before the installation of the granular soil columns. The obtained values between 60 and 80 kPa confirm the very soft soil and very low undrained shear strength of the soil.

Installation of Sand Columns in the Testing Pit

The sand columns were installed with full displacement of the soil during penetration of a pipe with closed toe as in the field. But in the model test a plastic pipe with a diameter of 315 mm was used and it was closed with a wooden part at the toe. At the final depth of 3 m the sand (0 - 2 mm) was filled into the pipe as shown in Fig. 19. Then the pipe was pulled out continuously under vibration leaving behind the lost toe and the sand column.

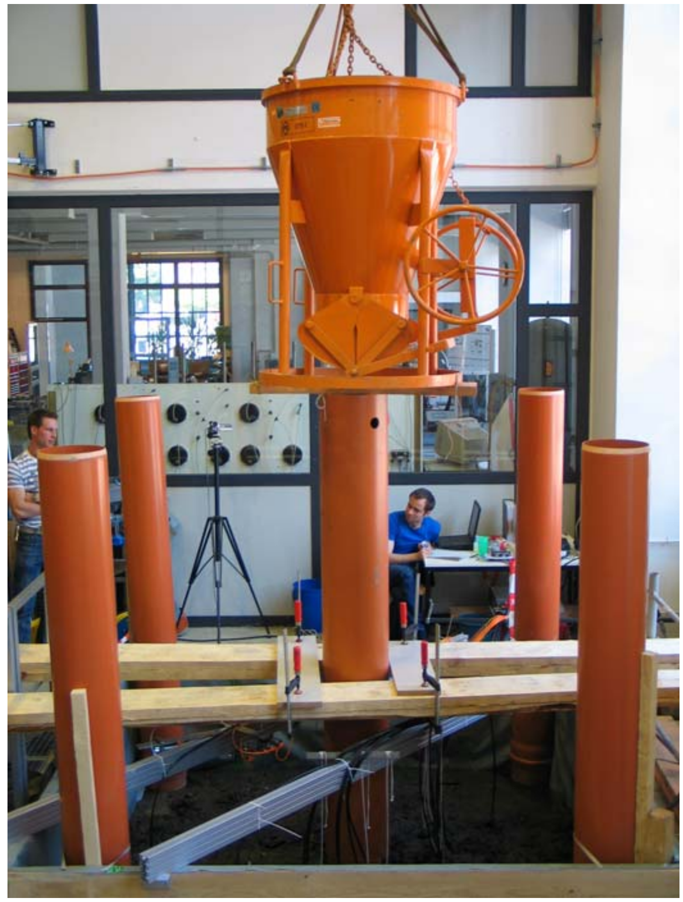


Fig. 19: Installation of a sand column in the geotechnical testing pit

The plan view area of the seven sand columns is approx. 10 % of the total area of the testing pit.

Measurements during the Installation of the Sand Columns

The installation of the sand columns was done on three days with a couple of days rest in between. First the centre column in axes B3 (cf. Fig. 13) was installed. Nine days later three columns in axes B5, A2 and C2 were installed. Finally again three days later the remaining columns in axes C4, A4 and B1 were installed. The results from measurements during this installation works are displayed in the following figures.

The mean values of the measured vertical displacements on the top edge of the organic silt and in three different depths are shown in Fig. 20. An upward movement of the surface of about 13 cm was measured resulting from the full displacement of the organic silt during the installation of three sand columns B5/A2/C2 and C4/A4/B1 respectively. The subsequent settlements are due to the consolidation as well as relaxation and creep effects in the soft soil.

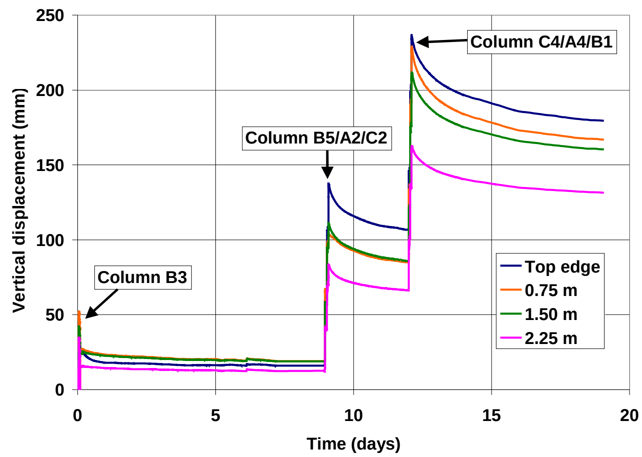


Fig. 20: Mean values of the measured vertical displacements during the column installation

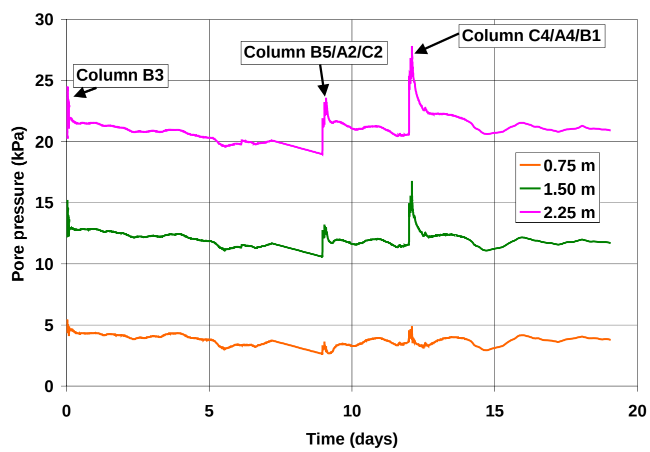


Fig. 21: Measured pore pressures in the organic silt during the column installation

The sand column installation works also effect the pore pressure generation in the soft soil as shown in Fig. 21. The maximum measured pore pressure increase during installation of three columns in a day was about 6 to 7 kPa in a distance of 0.3 to 1.0 m from the sand column. The amount of excess pore pressure increases with the number of installed sand columns and with the depth below the surface of the soil.

Within 90 minutes after the installation of the third column in a day already 50 % of the excess pore pressure was dissipated. The remaining excess pore pressure dissipated within the subsequent maximum 10 hours. But the dissipation time increases with the number of installed sand columns.

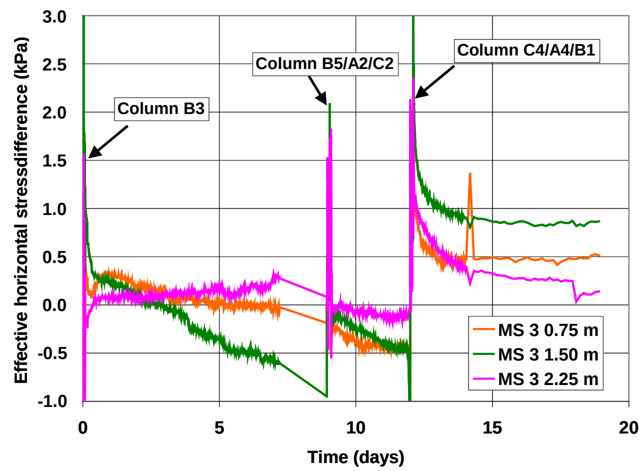


Fig. 22: Effective horizontal stresses in the organic silt during the column installation

Effective horizontal stress differences were evaluated using the measured total horizontal stresses and pore pressures as well. Their variation in time is illustrated in Fig. 22. The maximum stress increase reached 2 to 3 kPa with a minimum distance of 0.4 m between transducer and sand column. Reduction of the increased stresses with time is more slowly than the pore pressure dissipation due to the relaxation and creep effects of the soft soil.

<u>State of the Soil, Loading Stages and Measurements after the Installation of the Sand Columns</u>

Additional soil investigations were performed after the installation of the sand columns. Results from sounding tests in the columns using the Dynamic Probing Light (DPL) device characterized a very loose to medium dense state of the sand. Field vane shear tests in the soft soil between the columns did not reveal increased undrained shear strength. Water content measurements in the centre between sand columns did not expose significant changes, only slightly reductions compared to the measured values before column installation works. But the water content of the soft soil approx. 10 cm by the outside of the sand columns and in a depth of more than 2 m below top edge of the soil decreased clearly up to values between 200 and 100 %. That is a reduction of the water content of about 50 % compared to the initial state.

The surcharge load was applied in two stages. The first loading stage was started 17 days after the installation of the final sand column. Sand gravel was used as load and a total height of 1.4 m sand gravel was applied equivalent to about 21 kPa. The second load step - 35 cm sand gravel, i.e. 5.25 kPa - was applied 104 days after the first stage.

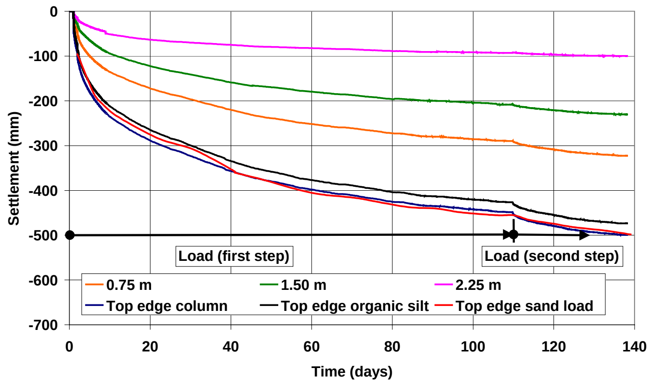


Fig. 23: Settlements after installation of granular columns and during the loading stages

Figure 23 shows the settlements over time starting from the first loading stage. The top edge settlements differ only slightly which is consistent and proves also the plausibility of the data. The maximum surface settlement due to the first load step reached 440 mm 110 days after column installation. That is equivalent to approx. 14 % vertical strain for the whole organic silt layer considering the heaving of the surface after column installation works. The settlements caused by the second load step show the same tendency but are less significant.

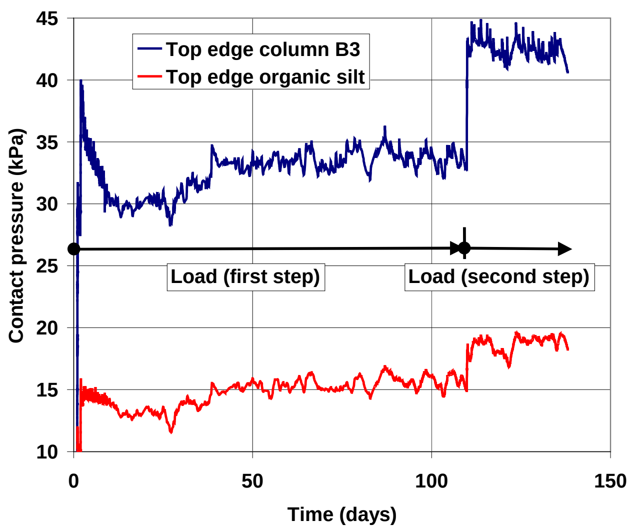


Fig. 24: Contact stresses between sand load layer and granular soil column as well as organic silt

Additional pressure transducers were installed on the surface of the organic silt as well as on the top of the sand columns (cf. Fig. 13) to measure the contact pressure distribution caused by the surcharge loading. Figure 24 displays the higher contact pressures on top of the sand columns compared to the top edge of the organic silt layer due to the higher stiffness of the sand columns. The stress ratio of the loads transferred to the sand columns vs. that to the organic soil is about 2.2.

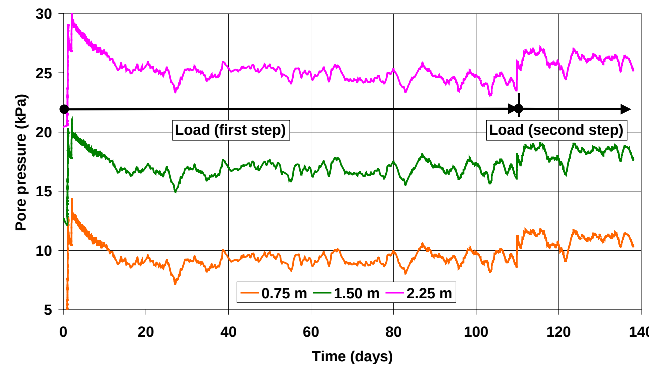


Fig. 25: Measured pore pressures in the organic silt during the loading stages

There was continuous dissipation of excess pore pressure measured over a period of 15 days after first loading application. The subsequent changes in pore pressure over time are due to changes in the atmospheric pressure. The end of primary consolidation due to the second load step is about 11 days after application of the surcharge loading. Therefore all settlements after these primary consolidation times are induced by creep effects.

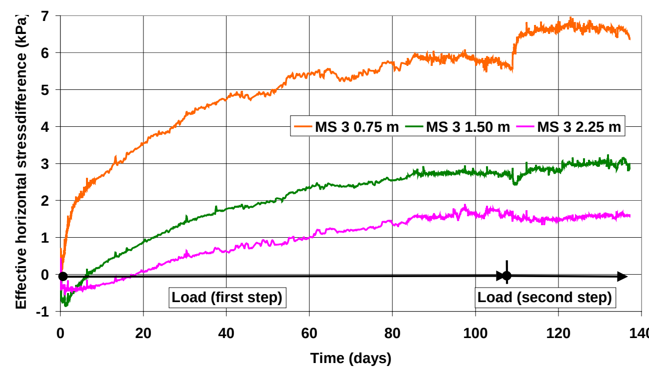


Fig. 26: Effective horizontal stress differences in the organic silt caused by the loading stages

Effective horizontal stress differences were evaluated again using the measured total horizontal stresses and pore pressures as well. Figure 26 shows the evaluated effective horizontal stress difference values with time for three points with different depth all in the centre line between two columns, i.e. in a distance of approx. 25 cm to the edge of the sand column (cf. Fig. 13). A significant increase of effective horizontal stresses after the end of primary consolidation results from the relaxation and creep effects of the soft organic soil. This effect is stress state dependent and therefore much more considerably in the first load step which was higher than the second load step.

CONCLUSIONS

The paper presents results from two projects where granular soil, i.e. sand, columns were used to improve very soft organic soil layers for the construction of road embankments on top of it. Numerical calculations, extensive in situ measurements as well as laboratory tests and a large scale model test were done to investigate the behaviour of the soft soil in conjunction with the sand columns in more detail.

The long term deformations of the soft organic soils are strongly influenced by their creep behaviour. Also the relaxation after the column installation works or the unloading of surcharge loads, i.e. the overconsolidation ratio and stress history, plays a crucial role for the long term behaviour of these soils. The density of the sand columns seems to be of minor importance for the soft soil-column interaction behaviour. The total settlement reduction of the improved soil compared to the natural ground conditions can attain about 50 % when using sand columns designed as in that paper.

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