Improvement of soft fat clay using rigid inclusions and vertical drains

Amélioration d’une argile plastique molle par inclusions rigides et drains verticaux

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ABSTRACT: In the case of a new road crossing in Germany with 1.5 to 7.0 m high embankments nearby the Danish border particularly soft clays were found 13 to 20 m deep below sea level. The undrained shear strength of the clay varied between 7 and 20 kN/m². The water content was almost 100 % and the organic matter below 6 %. The consolidation coefficient $C_v < 0.3$ m²/year is characteristics of a fat clay which requires a long time or tight spacing of vertical drains to consolidate. Due to stability risks, vertical wick drains were installed at a 0.5 m spacing in the part of the highest embankments, which were built in three load steps, each time waiting for 60 to 80 % consolidation degree before loading the next step. Even using 600 kN/m woven geotextiles, a total vertical settlement of around 1.5 m and up to 27 cm horizontal deformation were measured throughout one year of monitoring. These deformations were too high for the existing and running highway in the middle of the new projects. Therefore, full displacement concrete columns (rigid inclusions system CMC) were installed up to 22 m deep with load transfer platforms installed on top the inlcusions. In order to improve the installation process of the rigid inclusions, additional vertical drains were installed in the soft soil before the inclusions. Within the first two years, the area supported by the rigid inclusion experienced less than 2 cm of deformation, a proportionally small amount compared to the deformations recorded in the wick drain consolidation parts of the project.

RÉSUMÉ : Pour un projet d’une nouvelle route sur des remblais de 1,5 à 7,0 m de hauteur en Allemagne près de la frontière danoise, des argiles particulièrement molles ont été trouvés de 13 à 20 m de profondeur sous le niveau de la mer. La résistance au cisaillement de l'argile varie entre 7 et 20 kN / m². La teneur en eau est proche de 100% et la matière organique inférieure à 6%. Le coefficient de consolidation Cv <0,3 m² / an montre une argile plastique qui nécessite un long temps ou un réseau de drains verticaux très serrée pour la consolidation. En raison de calculs de stabilité, les drains verticaux ont été installés avec un espacement de 50 cm dans la partie des remblais les plus hauts, qui ont été construits en trois étapes de chargement, avec pour chaque étape des périodes d'attente de 60 à 80% degré de consolidation avant de la prochaine étape de chargement. Même avec l’utilisation de geotextiles de 600 kN/m, des tassements verticaux de 1.5 m et des déformations horizontales jusqu’à 27 cm ont été mesurés pendant une année de surveillance. Ces déformations sont trop importantes pour l'autoroute existante en exploitation près du nouveau projet. Des inclusions rigides (systeme CMC) ont été installées jusqu'à 22 m de profondeur avec différents matelas de répartition placés au dessus des colonnes. Afin d’améliorer le processus d'installation des inclusions rigides supplémentaires, des drains verticaux ont été installés dans le sol mou avant l’installation des colonnes. Au cours des deux premières années de construction, la zone supportée par les inclusions rigides a eu moins de 2 cm de déformation, une déformation relativement petite comparé avec celles enregistrées dans des zones du projet consolidées par des drains verticaux.

KEYWORDS: soil improvement, Controlled modulus columns (CMC), vertical drains

1 INTRODUCTION AND DESCRIPTION OF THE PROJECT

Large areas nearby the northern sea are nearly flat with elevations slightly above or under the sea level. Soft soil of silt, clay, mud and peat reach between five and twenty meters from the surface, before glacial sands are encountered.

The existing west coast highway B5 near the German city of Husum will be widened from two to three lanes in the future in order to improve traffic. The crossing between B5 and B202 was designed as a bridge project with high embankments located on the unconsolidated soft soils, typical at the flat costal region near the North Sea.

All traffic constructions bring new loads in form of dead- and live-loads to these soft soils. Without soil improvement methods large long-time settlements will occur, which often causes damages to the road during the construction or later on.

The traffic on the highways B5 and B202 in the site had to be maintained during the construction period and the existing road could not tolerate additional stability risks or settlements, especially when the 1.5 to 7 m high embankments are built directly beside the traffic. There are different stages to look at, but we will focus only on the western part with the highest dam nearby the bridge.

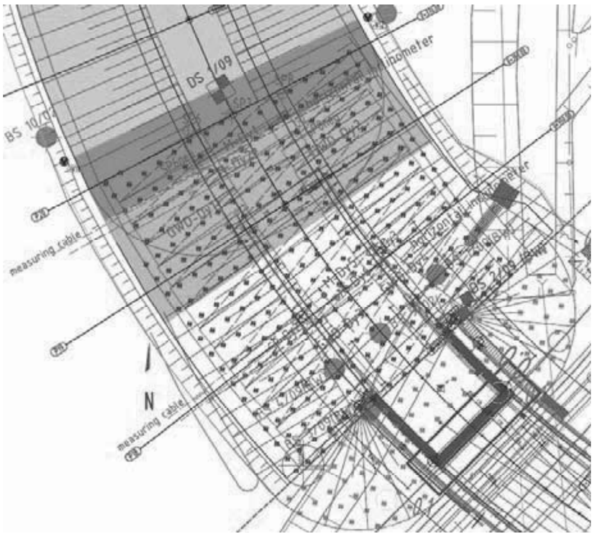

Figure 1. detail of the highest embankment west with the bridge abutment over the highway B5 (CMC close to bridge and coloured areas with vertical drains and preloading)

Due to stability and settlement calculations the foundation works took place according to the following sequence of works and according to the figure 2 below:

1. Installation of vertical drains in different spacings from a one meter thick sand working platform.
2. Preloading with three load steps with a distance of 30 m security and working space from the bridge and existing highway B5. (A)
3. The measured consolidation settlements shown in figure 8 fit with the given predictions according to figure 7. An additional strong woven geotextile layer of 600 kN/m tensile strength between the embankment and vertical drains had very little influence on the vertical inclinometer results with 27 cm of deformation as shown in figure 9.
4. After waiting for 1.3 m settlement (figure 8) a part of the embankment and preload was temporarily rebuilt in order to install the controlled modulus Columns CMC. (B)
5. The preload was brought back to the edge of the foundation systems between CMC and vertical drains area in order to optimize the settlement behaviour.(C)
6. Installtion of deep foundations for the bridge took place on driven concrete piles with additional sleeves sockets in the soft soils.
7. The CMC were installed between the driven piles afterwards, free of vibrations.

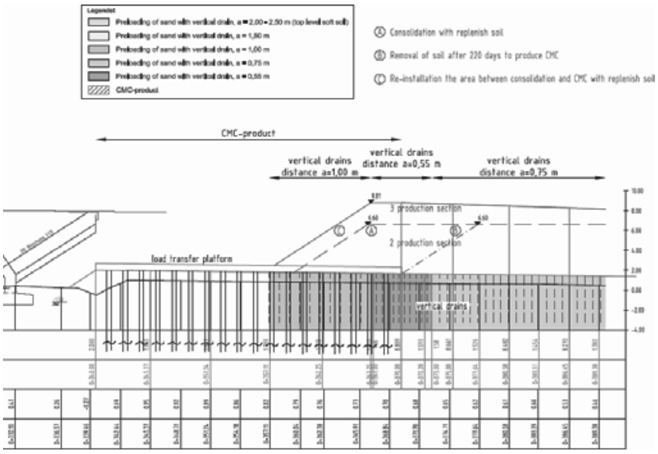

Figure 2. steps of consolidation and construction

The working sequence with different steps was necessary because of stability calculations and the wide influence of the settlements during the consolidation. The CMC brought the following advantages:

- short installation period to complete the project on time
- the vibration free technique allows to work close to the piles of the bridge
- The settlements of the embankment support on CMC with a stiff load transfer platform are compatible with the bridge abutment

2 SOIL-PARAMETERS

After the first part of the soil investigations with several borings (BS) and cone penetration tests (CPT) it was clear that there was a problem of stability and consolidation time due to the presence of fat clay in the upper soft soil layer. The project can be modelled with two layers of soft soils divided by a loose sand layer in between. This reaches 13 m up to 22 m in the deepest parts from the surface.

The undrained shear strength c_u in the soft soil from the results of shear vane tests multiplied with factors of 0.5 to 0.65 are linked to the plasticity according to Bjerum standard DIN 4094-4, Part 4 (Deutsche Institut für Normung 2002). In additon to borings, several laboratory testing (water content, organic matter and plasticity index) as well as several load-settlement tests were performed.

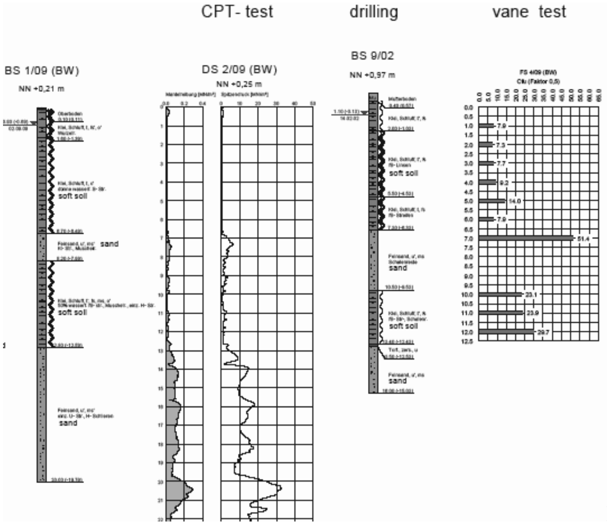

Figure 3. boring, cone penetration test and shear vane test in the detail area bridge west

The vane tests showed an undrained shear strength of c_u = 6 to 8 kN/m² near the bridge and an undrained shear strength of c_u = 12 to 20 kN/m² in other parts of the project. This was one more reason to select a CMC foundation nearby the bridge in the area of the lowest undrained shear strength.

Following this decision and the results of soil investigation and laboratory the geotechnical engineers assumed an undrained shear strength of c_u = 12 kN/m² in vertical drain areas. The representative soil parameters for the calculation of consolidation and stability in the project are given in the following table.

Table 1 . soil parameters for the calculation of consolidation and stability in the coloured drain areas

soil properties / soil	density γ_k/γ_k' [kN/m³]	shear strenght φ'_k [grade]	Cohesion $C'_{,k}$ [kN/m²]	$C_{u,k}$	Modulus $E_{s,k}$ [MN/m²] 50-100 kN/m²	Consoli-dation coeffi-cient c_v [m²/s]
fill sand	18/10	30,0	---		60	$6{,}0 \cdot 10^{-1}$
soft soil, clay [top level]	14/4	17,5	15	12	0,8	$8{,}0 \cdot 10^{-9}$
soft soil, silt top level	15/5	20,0	10	12	0,8	$2{,}0 \cdot 10^{-8}$
sand	18/10	27,5	---		25	$2{,}5 \cdot 10^{-3}$
soft soil, silt (Bottom level)	16/6	20,0	10	20	2,0	$1{,}0 \cdot 10^{-7}$

3 SOILIMPROVEMENT TECHNIQUES

3.1 *Vertical drains*

Prefabricated vertical drains were installed in different spacings with lengths between 15 m (corresponding to the conditions in figure 3) and 22 m in other parts of the project. It was necessary to pass the intermediate sandlayer in order to place the vertical drains in the glacial sand below the second layer of soft soil. The small spacings in this project were justified by the step loading and the presence of fat clay in the upper layer of soft soil with special low permeability and corresponding primary consolidation coefficient.

3.2 *Controlled Modulus Columns CMC*

The controlled modulus columns CMC are well adapted to installation in soft soils. The full displacement auger acts as a casing and maitain the right borehole diameter over more than two meter length. Concrete pressure and adequate volume are monitored and maintained throughout the concreting phase, which is very critical in very soft soils. The typical piling standards give a minimum limit of 15 kN/m² undrained shear strength to use for cast-in-place-concrete.

By the standard DIN EN 12699 (Deutsche Institut für Normung 2001) above c_u = 15 kN/m² the minimal distance between full displacing elements is linked to the undrained shear strength of the soils. Critical distance is only relevant during the concrete curing period.

Compared to vibrating techniques, CMC are usually faster to install and can be performed in softer soils with lower undrained shear strength. There are several references with CMC-installation directly adjacent to freshly grouted CMC under $c_u < 15$ kN/m² conditions. In this project the CMC have been first successfully checked under conditions with the lowest c_u-values by integrity tests and dynamic pile tests. Loads larger than 500 kN could be tested with a factor of safety larger than 2 FOS on the CMC, drilled into the glacial sand layer.

On part of the project, the process of installing additional CMCs close to nearby fresh CMC was improved through the installation of vertical drains in-between the CMC. Immediately after the CMC installation the water starts to flow out of the vertical drain even at the top of the sandy working platform. A continuous flow for several hours up to one day and the volume of water collected show an efficient fast additional consolidation.

Compared with other CMC areas the heave of the working platform and the excessive over-consumption of concrete, normally increasing with the thickness of softsoil, could be reduced by the additional intermediate vertical drains.

Figure 4. installation of CMC combined with vertical drains and pore-water on the platform

4 CALCULATIONS AND PREDICTIONS

4.1 *Consolidation and stability calculations in the areas receiving vertical drains*

Initially, a total settlement of 1.29 m was calculated in the area west of the bridge. The time-settlement curves for both primary and secondary consolidation are shown below on figure 5.

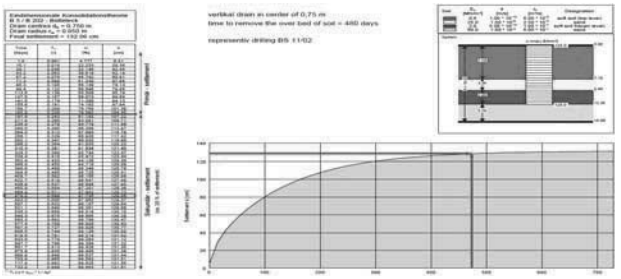

Figure *5.* 129 cm of settlements within ½ year of primary consolidation with vertical drains spacing of 0.75 m

The stability calculations are based on undrained shear strength c_u and required to build the embankment in three steps of loading with berms and twice waiting for the sufficient degree of consolidation necessary. According to (Chaumeny, Kirstein and Varaksin 2008) the shear strength was calculated using the following relation to the degree of consolidation:

$$\tau = U\,(\sigma \tan \varphi' + c) + (1-U)\,c_u \qquad (1)$$

U: degree of consolidation
σ: total load at a given depth
φ': internal friction angle
c: final drained cohesion
c_u: undrained shear strength

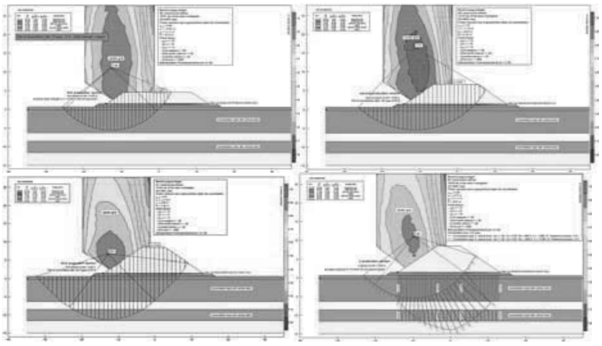

Figure 6. stability calculation of three loading steps and control calculation of the final situation

For this project c = c_u in formula (1) as improvement Δc_u was added to the basic c_u value in the stability calculations.

$$\Delta c_u = U\,\sigma \tan \varphi' \qquad (2)$$

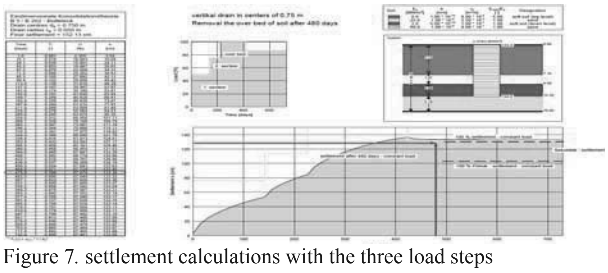

Figure 7. settlement calculations with the three load steps

Field measurements and the stability analysis in final configuration based on φ', c and porewater pressure were in good agreement with the calculations using the improved undrained shear strength.

4.2 *Controlled Modulus Columns CMC*

Due to the presence of very soft soils, the CMC are designed to take the full load of the embankment, neglecting the small load bearing capacity of the soil in between the inclusions. With 500 kN characteristic load per CMC, the calculated settlement at the top of each CMC is very similar to the settlement of the piles under the bridge.

Nevertheless, below the embankment, there is no concrete slab or rigid structure like for the foundation of the bridge. Reinforced earth with galvanized steel was designed to hold the large horizontal forces of active earth pressure. Because of the large geotextile deformations during the consolidation period, as shown in the following monitoring results, the decision was made to use a stronger more rigid construction with nearly no deformation. Compared with plastic geotextiles, the steel grid material has only very small elastic deformations, and as a result limiting the horizontal deformations of the embankment. Through the addition of some gravel in parts of the sandy load transfer platform LTP, the friction between LTP and CMC was greatly increase and nearly no deformation was necessary to mobilize the friction of the LTP.

5 MONITORING RESULTS

5.1 *Wick drains*

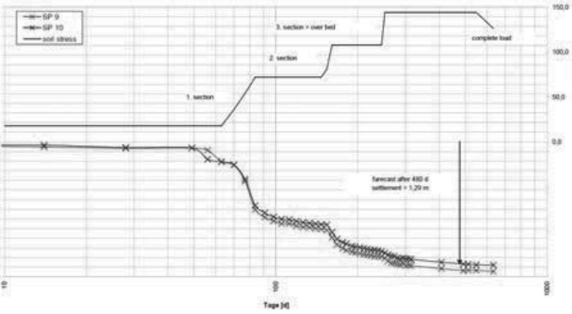

Figure 8. measurement at the settlement plates SP 9 und SP10.

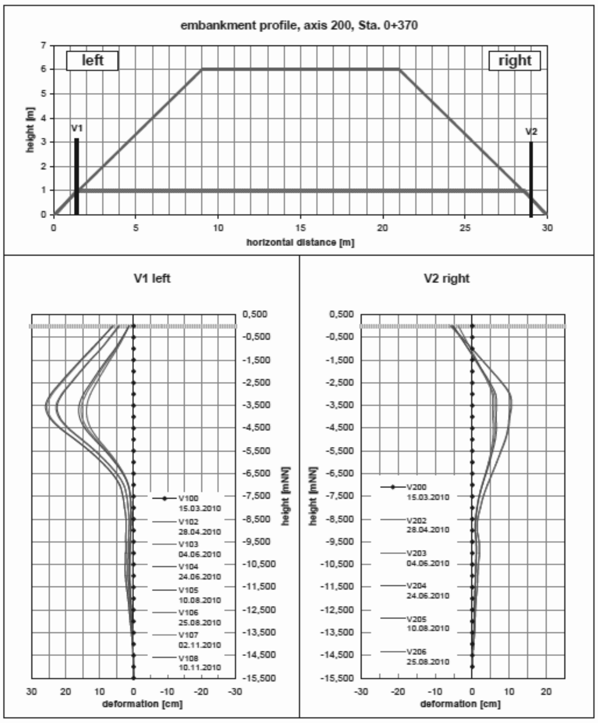

Figure 9. vertical inclinometer results at the 7 m high damm with drains and 600 kN/m vowen geotextile

The measured settlements during the consolidation process in figure 8 follow very closely the predictions shown in figure 7. An additional strong geotextile layer of 600 kN/m tensile strength between the embankment and the vertical drains had 27 cm of deformation measured with vertical inclinometers.

5.2 *Controlled Modulus Columns CMC*

Several measurement systems were installed between the CMC and the reinforced earth in the load transfer platform. The instruments show an almost perfect full stress concentration of the load on the CMC and less than one centimetre of horizontal deformation. Figure 10 shows the cross section and the 5 vertical deformation measurements over a period of 2 years. The horizontal inclinometer was laid across six marked CMC-columns (figure 1 and figure 9). A settlement of one centimetre of the top of the CMCs and two centimetres in-between CMC in the reinforced earth steel construction were measured. There was a good agreement between the calculated values of the settlement and the results of the monitoring.

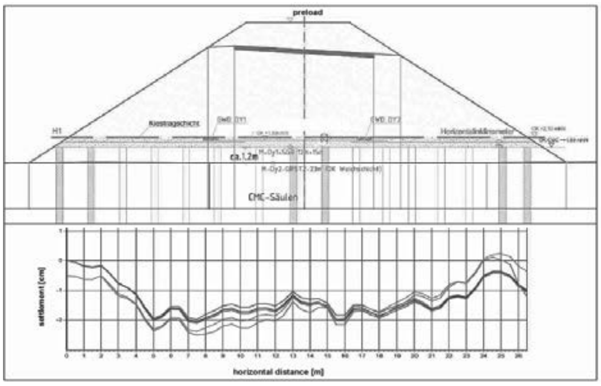

Figure 10. horizontal inclinometer results with arround 1 cm of CMC settlements and 2 cm of reinforced earth settlements

6 SUMMARY AND CONCLUSIONS

Soft and fat clay were found at the B5 / B202 road crossing. Additional soil investigations and laboratory tests were performed to be able to complete a proper design, regarding stability and consolidation time.

Oedometer consolidation tests allowed to precisely predict the movements during the consolidation processes that were accelerated by the use of vertical drains at different spacings. Large deformations of up to 1.5 m of settlements and 27 cm of horizontal displacement were experience and closely match the calculations and show that it was the right decision not to place the highest embankment directly on the softest soil beside the bridge over the running traffic on the highway B5.

Vibration free CMC in combination with reinforced earth allowed to construct this high embankment with less than two centimetre differential settlements to the piled bridge.

With a careful planning of the work within the overall construction schedule, detailed design combined with an extensive monitoring program, economic soil improvement techniques can be combined with deep foundations in one project even on very soft soil can be treated successfully.

7 REFERENCES

DIN Deutsches Institut für Normung, 2002, DIN 4094-4: Subsoil – field testing – part 4 : Field vane test.

DIN Deutsches Institut für Normung, 2001, DIN EN 12699: Execution of special geotechnical work - Displacement piles; German version

J-L Chaumeny, J.F.Kirstein, S. Varaksin, 2008, An experience of consolidation of extremly soft mud for one of Europe's largest projects "The AIRBUS A-380" factory in Hamburg, Glasgow.