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Vacuum Consolidation trials to validate strength increase of peaty subsoil for dike stability

Essais de consolidation vacuum pour valider une augmentation de la résistance du sous-sol tourbeux pour la stabilité des digues.

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ABSTRACT: There is an increasing demand in the Netherlands for innovative solutions to increase the (macro) slope stability of dikes. This is mainly caused by new insights into the calculations method, increased safety regulations with climate change related higher design water levels, limited working space and a large amount of interfaces. Vacuum consolidation techniques have proven their efficiency in infrastructural and reclamation projects to reduce residual settlements. However, the technique has not been used with the sole intention to increase the soil strength in dike design before. It can have important advantages over traditional solutions. This paper presents the factual data and findings of vacuum consolidation trials performed on the Markermeerdijken project in Schardam, the Netherlands. Two trial areas were set up using different vacuum consolidations systems to consolidate the peaty subsoil: a traditional vacuum system and the Beaudrain-S system. The trials were performed to validate the (undrained) shear strength increase of the peaty subsoil. Several in situ tests and lab tests on subsoil samples were performed before and after consolidation such as DSS, Triaxial and (spherical) CPT testing. Before installation of the equipment only a limited working platform of relatively lightweight flugsand was applied to research solely the effects of the vacuum pressure on the strength increase. During the trials vacuum pressures were measured in the soil and in the drains using piezometers. Additionally, settlements were measured during consolidation as well as swelling after consolidation. For both areas a total pumping time of 13 weeks was applied and settlements up to 1.5m were measured under vacuum pressures of up to 70KPa. The laboratory test results of subsoil samples showed a considerable increase in undrained shear strength, corresponding to theoretical models.

RÉSUMÉ: Il existe aux Pays-Bas une demande en hausse d'idées innovantes afin d'augmenter la (macro) stabilité des pentes de digues. Ceci s'explique par une meilleure compréhension des méthodes de calculs, de règles de sécurité améliorées prenant en compte la montée du niveau des mers avec le réchauffement climatique, d'espace restrient de travail ainsi qu'un nombre important d'interfaces. Les méthodes de consolidation vacuum, ou sous-vide, ont prouvé leur efficacité sur des projets d'infrastructures et de construction sur la mer pour réduire les tassements résiduels. Néanmoins, la technique n'a pas encore été employée dans l'unique intention d'améliorer la résistance du sol dans le design des digues. Elle peut avoir de solides avantages par rapport aux techniques traditionnelles. Ce document présente les données factuelles et résultats d'essais de consolidation vacuum réalisés sur le projet Markermeerdijken à Schardam aux Pays-Bas. Deux zones d'essais ont été mises en place avec différents systèmes de consolidation : un système de consolidation vacuum classique et un système Beaudrain-S. Les essais ont été réalisés pour investiguer l'augmentation de la résistance au cisaillement (non-drainée) du sol tourbeux. Plusieurs essais in-situ et en laboratoire ont été réalisés sur des échantillons de sol, avant et après consolidation. On cite ici les tests de cisaillement simples, les essais triaxiaux et les tests CPT à pointe spherique. Avant installation des équipements, l'étude s'est d'abord focalisée sur une surface limitée de flugsand pour comprendre uniquement les effets de la pression à vide sur l'augmentation de la résistance. Au cours des essais, les pressions à vide ont été mesurées dans le sol et dans les drains en utilisant des piézomètres. Parallèlement, les tassements furent mesurés pendant la consolidation ainsi que le gonflement du sol après consolidation. Dans les deux zones d'études, un temps total de pompage de 13 semaines a été respecté, et des tassements jusqu'à 1.5m ont été mesurés sous des pressions à vide jusqu'à 70 kPa. Les essais conduits en laboratoire sur des échantillons de sol ont montré une considérable augmentation de la résistance au cisaillement non-drainée, en adéquation avec les résultats théoriques.

Keywords: Vacuum consolidation, Soil Improvement, Dike stability, Peat, Undrained Shear Strength

1 INTRODUCTION

In the Netherlands a large dike improvement program, called HWBP (high water protection program), of several billion euros is executed until 2050. In this program there is an increasing demand for innovative solutions to improve the macro stability of dikes in a time and cost efficient way. The improvement program is caused by several factors such as climate change related water level rise, increased safety regulations and new calculation methods. Innovative solutions are demanded for reducing costs, decreasing time for dike improvement projects, limited working space, preservation of often historical landscape and an increased amount of project interfaces. Therefore within the HWBP large research programs are developed, among which the POVM (research project on macro stability). The POVM is dedicated to slope stability. In the POVM several research initiatives are initiated. One of them is the use of vacuum consolidation to increase the strength at the toe of the embankment to reduce the impact of a dike strengthening project on the landscape and reduce material use and transport.

Vacuum consolidation is well-known in infrastructure projects to reduce the residual settlements and horizontal deformations after construction and the ability to apply a faster surcharging schedule due to the faster increase of the shear strength of the cohesive subsoils, but it is less known in the application to only increase the strength at the toe of the dyke. The strength increase has the effect that berms of the dike can be obsolete or remain lower which limits the use of embankment materials and has a far lower impact on the often historical landscapes. This latter was of high importance in the Markermeerdijken dike reinforcement project, where a reinforcement is required in the famous and historical peat landscapes and dike villages just north of Amsterdam, the Netherlands.

The potential advantages of the system led the Markermeerdijken project, an alliance between Waterboard Noord Hollands Noorderkwartier and contractor Boskalis, to initiate a vacuum consolidation trial together with the research program POVM and ground improvement contractor Cofra.

For this trial the specific goal of the POVM was to create guidance for the technique regarding calculation methods, get proof whether the increase of the pre-consolidation stress and the shear strength, after removal of solely a vacuum pressure, is permanent and to research the validity of the SHANSEP method,

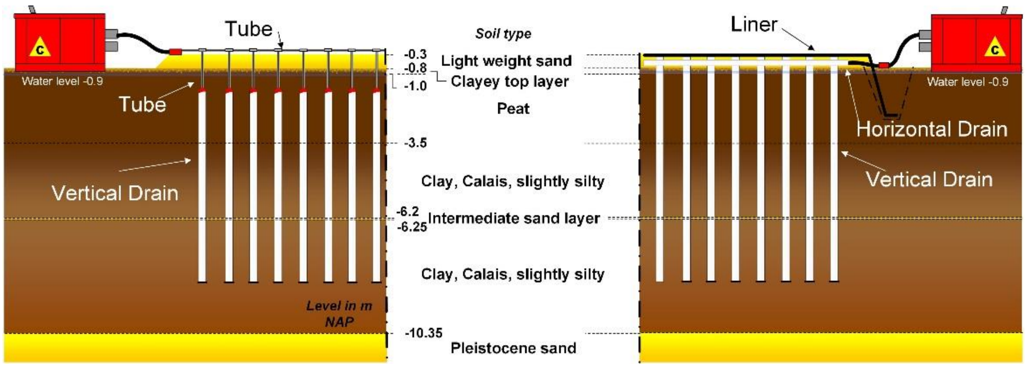

Figure 1 – Cross section of techniques, left: Beaudrain-S, right: traditional vacuum system

Lad & Foot (1974) to calculate the strength increase of the vacuum.

This paper will provide an overview of the site and used vacuum methods after which the sequence of works including field measurements and site investigation results are described.

2 VACUUM METHODS

Two vacuum consolidation techniques were selected for the trial: Beaudrain-S and the traditional liner vacuum consolidation system. Figure 1 provides an illustration of both techniques together with the local soil profile of the site.

The Beaudrain-S system consists of individual drains that are combined from a PVD section and a tube section. The PVD length is designed such that it is only applied in the compressible layers below the ground water. The remaining soil layers, all layers above the water table but also those that cause a risk for air or large water inflow are crossed using the tube. On the surface the individual tubes of the combined drain-tube drain are connected using T-couplings and tubes, which are in turn connected to a vacuum pump at the edge of the field.

The traditional liner vacuum system uses conventional PVD, horizontal drains and a membrane/liner. The vertical drains are installed from a permeable working platform and connected at the surface to horizontal drains, which are its turn connected to a closed collection drain. The collection drain is connected to a vacuum pump. The whole area is sealed by an impervious membrane/liner which is buried on the edges of the area using peripheral trenches below the water table.

3 SITE OVERVIEW

3.1 Location and layout

The trial area was located near Schardam and consisted of two sections to test both systems described in chapter 2. The area was chosen on the basis of preliminary site investigation. The sections were 17.5m x 17.5m each. Figure 2 and figure 4 give an overview of the area. The phreatic line at the trial site was close to the existing surface level of NAP -0.8m at NAP -0.9m.

3.2 Site investigation

Before commencement of the installation of the vacuum systems, a second detailed site investigation campaign was initiated consisting of CPT‘s, boreholes and Ball penetrometer tests.

The CPT‘s were used to determine soil properties, layering and a check on the occurrence of sand layers. The data was also used to determine the BeauDrain-S drain and tube length.

The boreholes have been performed to obtain soil samples from the different cohesive soil layers. On these soil samples compression (CSR), Direct Simple Shear (DSS) and triaxial tests have been performed. The compression tests were performed to determine the initial consolidation coefficient, the initial pre-consolidation stress and thereby the Over-Consolidation Ratio and the SHANSEP parameter m. The DSS tests were used to determine the SHANSEP parameter S, the initial shear strength su at the in-situ terrain stress.

A relative new test, the Ball penetrometer test, has also been performed to determine the undrained shear strength in detail. The test is similar to a CPT test, but the cone tip is a spherically shaped ball tip of 8-10 times the normal cone diameter. The test has an improved accuracy and resolution in soft soils. The undrained shear strength can be estimated from Ball penetrometer data that needs to be correlated with laboratory testing. In this case the undrained shear strength values, as defined from the DSS and CAU tests, were correlated with the corresponding values from the Ball penetrometer tests at similar depths.

4 INSTALLATION

Due to the very soft soil conditions and high water table at the site a special working method for installation of the drains was to be applied to minimize the risk for squeezing and stability issues. This was also required as the research objective was to investigate the effect of solely the vacuum pressure. It was therefore chosen to apply a light weight working platform of approx. 0.5m using Vulcanic light weight flugsand on top of a light geotextile. On top of the working platform timber matts were applied for load spreading of the light hydraulic excavator. In both sections the vertical drains have been installed in triangular spacing of 1m. Installation depth was up to 2m above the Pleistocene sand (NAP -8.7m).

Figure 3 – Traditional liner vacuum system, left: vertical drains connected to the horizontal drains, right: liner in trench surrounding the area.

For the section in which the traditional liner vacuum consolidation was applied an overlength of vertical drains was used. These were connected to the horizontal drains. Finally, a trench was excavated in which the liner was placed below the water table and backfilled. Please refer to figure 3.

Installation was performed without any problems.

Figure 2 – Trial area with the traditional vacuum system (left) & the Beaudrain-S system (right)

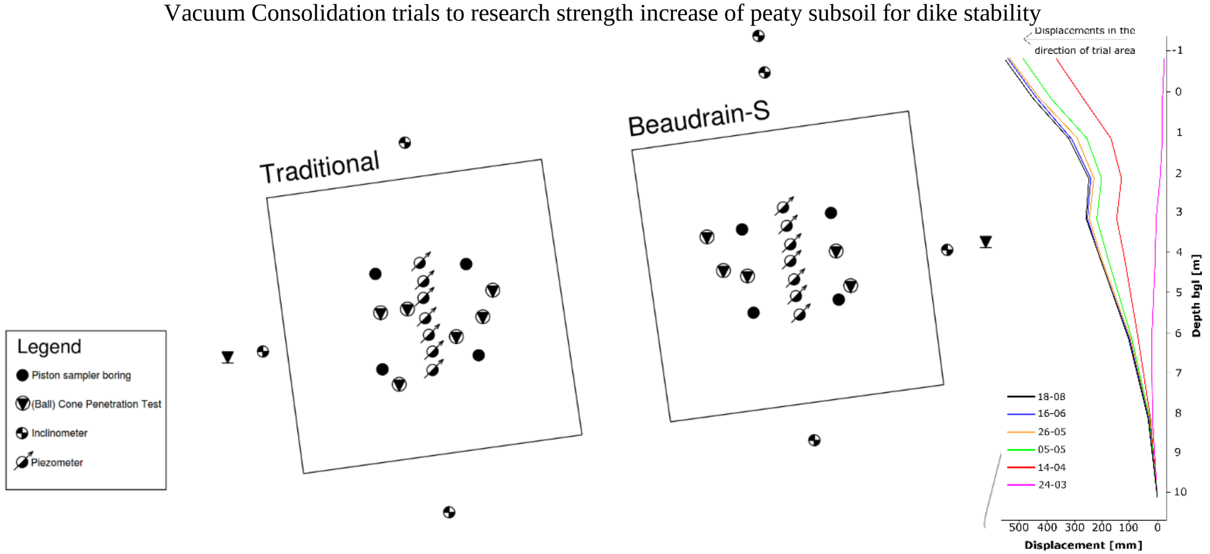

Figure 4 – Left: Overview of monitoring + test locations, Right: inclinometer readings close to BD-S area

5 MONITORING DURING CONSOLIDATION

5.1 Monitoring Equipment

Monitoring equipment has been installed within and around each trial area: settlement plates (4 in total, 2 per area), inclinometers (7 in total) and piezometers (14 in total, 7 per area) from which 2 are installed inside the vertical drains. Figure 4 gives an overview of the monitoring equipment. Special arrangements had to be made for the monitoring equipment and cables to make sure no leakage could occur or damage to the liner by too high deformations. The Beaudrain-S trial section did not have this issue, refer to figure 5 in which the monitoring equipment is still visible during consolidation.

Figure 5 – Beaudrain-S section with monitoring equipment (after some days of consolidation).

5.2 Settlements

The settlements have been monitored continuously over time in both area‘s using settlement cells, placed on the surface, on the basis of changing water pressures. The settlement is an important measure for the degree of consolidation of the subsoil. Two settlement plates were applied per section/technique to check the cell measurements. One settlement plate was located on the edge of a section and one in the middle.

The measured settlements are presented in figure 6. It can be clearly interpreted that the measurements in the middle of the sections show the most significant settlement compared to the settlement plates on the edge. Both systems also show similar behavior. Settlements of approx. 1.1 – 1.5m have been measured over the consolidation period of 90d. After release of the vacuum (end of June) a clear swelling effect is observed over time. A volume change of approx. 210m3 has been induced by the Beaudrain-S area and just over 200m3 for the traditional vacuum area.

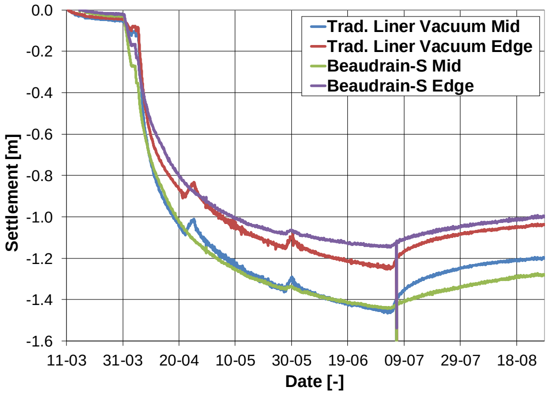

Figure 6 - Settlements over time during vacuum consolidation

5.3 Inclinometers

The inclinometers were placed at several distances from the vacuum areas to research horizontal deformations with distance both during and after the test, see figure 4. The effect of the vacuum pressure is that deformations are in the direction of the vacuum area as there is no driving force of any surcharge. For the locations close to the edge of the trial horizontal field deformations were measured up to approximately ~0.6m. During the trial it was not investigated if settlement compensation, that would cause an outwards deformation, would cancel the inward deformations from the vacuum consolidation and if it is a potential method to control horizontal deformation, which can be beneficial for the surroundings.

5.4 Water pressures

Water pressures inside the ground have also been monitored during and after the trial to research the time dependent behavior of effective stress before and after the vacuum period. This has been done by continuous measurements and vibrating wire piezometers. The piezometers have been divided over the different soil layers and could measure both positive and negative pressures. One meter has also been placed in the permeable layers below the soft soils and used as a reference measurement. Additionally, two piezometers have been installed inside the vertical drains at the bottom of the drain to measure the actual vacuum pressure that was applied to the soil. This pressure is always different from the pump pressure, due to height differences between the pump and the water table and the flow losses in the system. The pumps achieved a fairly constant vacuum pressure of about 90KPa in the Beaudrain-S area. For the traditional area a gradual increase in pump pressures was observed from 70 to 90KPa over the course of 2 months after which it was fairly constant.

The measurements taken in the traditional vacuum area show a water pressure drop in the silty clay layer of about 60kPa. The water pressure drop in the Peat is approx. 20kPa. In the Beaudrain-S area this is similar with values of 60kPa and 70kPa in the silty clay and 35kPa in the Peat. Please refer to figure 7 for an overview of water pressures in the Beaudrain-S area. The water pressure drop in the clay is more significant for both trial areas and comparable to the water pressure lowering inside the vertical drains which was between 60-70KPa. The lower value found in the peat was not expected, but can possibly be attributed to gas in the peat or a different ratio between the vertical and horizontal permeability than initially assumed. The slightly lower achieved vacuum pressure in the traditional vacuum area is likely to be caused by a slower buildup of the vacuum and the breakdown of the pumps.

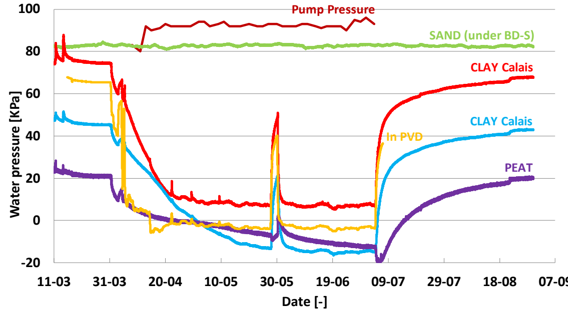

Figure 7 - Water pressures over time Beaudrain-S area

6 POST CONSOLIDATION TESTING

The last phase of the site investigation was performed within 7 days and after 100 days of the shutdown of the pumps and the end of the vacuum pressure. During this investigation stage the ball penetrometer tests and additional boreholes have been performed to research the changed post-consolidation stress and thereby the OCR value, as well as the SHANSEP parameter m and the adjusted shear strength. Additionally, site investigation approx. 1000d after the end of the vacuum pressure still has to be performed in 2019.

6.1 Ball penetrometer results

Figure 8 shows a typical ball penetrometer results before start of the trials (t=0), 7d (t=7) and 100d (t=100) after the vacuum consolidation has been applied and removed on the Beaudrain-S section.

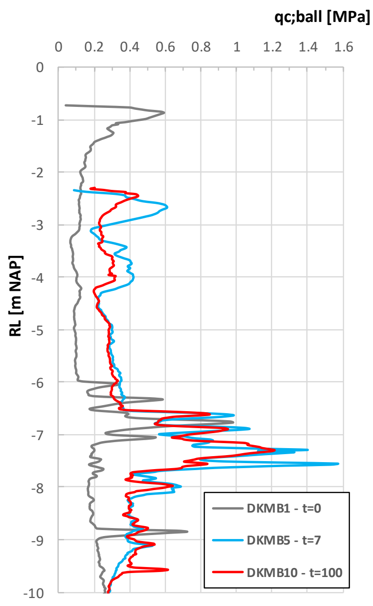

Figure 8 – Ball penetrometer results before and after consolidation in the Beaudrain-S section

Clearly the ball cone penetration resistance has increased by approx. 200-250% after the vacuum consolidation period. There is a slight decrease in penetration resistance over time in the top peat layer, but the cone resistance is still well over initial value. This can also be attributed to local variability in the subsoil (a post test is performed at a slightly different location). The cone penetration resistance is correlated to a strength increase in the soil.

6.2 Pre-consolidation stress and undrained strength

The pre-consolidations stress increase has been determined directly based on compression tests on soil samples. Soil samples were obtained from the boreholes before the vacuum and within 7 days after the vacuum has been removed. Note that the distance of the boreholes to the vertical drains influences the pre-consolidation stress. The boreholes were therefore located in the theoretical centre of the drainage grid, which is the most conservative location in terms of strength increase. However, due to the settlement the exact location of the drains relative to the boreholes are unknown.

Next to laboratory testing the pre-consolidation pressure has also been determined indirectly by using a correlation with the ball cone resistance.

From the achieved water pressure lowering, the initial stress level and pre-consolidation pressure the increase in pre-consolidation pressure has been estimated using known calculation methods. The outcome of the calculation showed that the shear strength of the peat layer in the traditional vacuum area increased from 11 kPa to about 25kPa and in the Beaudrain-S area from 11 to about 40kPa. For the silty clay layers this was in both areas an increase from 20 to 70kPa.

The calculated increase in pre-consolidation stress in both the peat and clay layers correspond fairly well with the increase that was found in the laboratory tests (direct measurement based on a K0-CRS-tests) and field tests (indirect measurements based on ball-penetration tests), please refer to figure 9. The pre-consolidation stress is the derived from ball-penetration test by using the correlations (n_{ball}) between the undrained shear strength (derived from DSS-tests) and the ball-resistance. Within the SHANSEP method the pre-consolidation stress can be calculated by the undrained shear the S-ratio give and the actual effective stress.

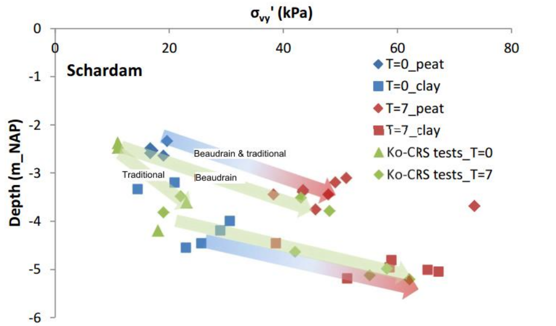

Figure 9 – Direct (K0-crs test, green line) & indirect pre-consolidation stress determination (Ball-penetration test, red and blue lines) for different soil layers at t=0 and t=7 (within 7d after ending vacuum), source: POV-M (2017)

Triaxial and DSS tests have been performed to determine the strength increase. These results have been compared to the SHANSEP method and to the correlation with Ball cone resistance. Results were found to be comparable, please refer to figure 10 for an example.

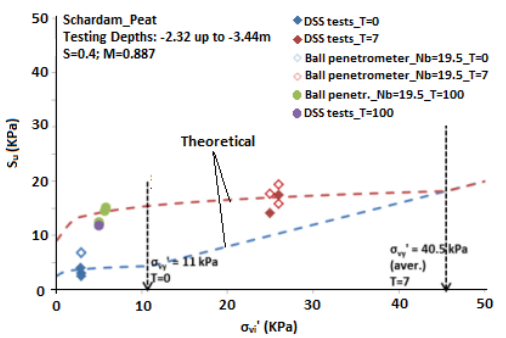

Figure 10 – Example of Beaudrain-S area (Peat): DSS results, theoretical SHANSEP line & correlation Ball cone resistance, source: POV-M (2017)

7 CONCLUSIONS

Vacuum consolidation trials using two different vacuum techniques have been performed in Schardam, the Netherlands. The trials have shown that both vacuum consolidation techniques are an effective method for the shear strength increase of the subsoil in dike reinforcement project. It has been proven that the vacuum pressure alone causes a strength increase.

The strength gain can be well determined using the SHANSEP method. Field and laboratory tests have shown that pre-consolidation pressure increase and the undrained shear strength is permanent. The increase in the Clay layers was more pronounced than the increase in the peat layers.

Based on the results and conclusions vacuum consolidation is anticipated to be used as an innovative technique for certain sections of the dike in the „Markermeerdijken“ project.

8 ACKNOWLEDGEMENTS

The trial has been performed as a collaboration between several parties: The alliance Markerkmeerdijken between the water Board „Hollands Noorderkwartier“ and Boskalis. Fugro has performed the site investigation and the laboratory tests together with Deltares. The vacuum system has been installed and maintained by Cofra. The full tests and interpretation has been described in the (Dutch) report of the POVM (POVM 2017). This paper uses several findings and conclusions from this report. Thank goes out to all parties and persons involved for making this successful test possible.

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