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The ventilated well method as an alternative solution for dewatering of soft soils

La méthode du puits ventilé comme solution alternative pour l'assèchement des sols mous

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ABSTRACT: The efficient dewatering and consolidation of soft soil is still one of the great challenges in geotechnical engineering. Many methods have been developed over the recent decades to accelerate the dewatering and the consequential consolidation of soft soils. The contribution introduces the Ventilated Well Method (VWM) as an alternative solution for this problem. The VWM takes advantage from wells inserted in the ground that are ventilated with air of reduced relative humidity. Evaporation is caused at the wall of the well while the dry air travels up the well. The consequentially induced water flow reduces the pore water pressure around the well creating an increase in effective stress that not only enforces volumetric strain on the soil, but also increases the strength right from the beginning of the operation. The contribution introduces the VWM, presents results of laboratory investigations, gives an overview of ongoing large-scale investigations and discusses the practical operation of this method.

RÉSUMÉ : L'assèchement et la consolidation efficaces des sols meubles restent l'un des grands défis de l'ingénierie géotechnique. De nombreuses méthodes ont été développées au cours des dernières décennies pour accélérer l'assèchement et la consolidation consécutive des sols mous. La contribution présente la méthode des puits ventilés (VWM) comme solution alternative à ce problème. Le VWM profite de puits insérés dans le sol qui sont ventilés avec de l'air à humidité relative réduite. L'évaporation est provoquée au niveau de la paroi du puits tandis que l'air sec remonte le puits. Le débit d'eau induit en conséquence réduit la pression de l'eau interstitielle autour du puits, créant une augmentation de la contrainte effective qui non seulement exerce une contrainte volumétrique sur le sol, mais augmente également la résistance dès le début de l'opération. Cette étude présente le VWM, présente les résultats d'investigations en laboratoire, donne un aperçu des investigations en cours à grande échelle et discute du fonctionnement pratique de cette méthode.

KEYWORDS: Dewatering, consolidation, evaporation, ground improvement, soft soil.

1 INTRODUCTION

The efficient consolidation or dewatering of soft soil for improving its compressibility and bearing capacity is still one of the great challenges in geotechnical engineering. Conventionally, surcharge is applied to consolidate the ground in combination with prefabricated vertical drains (PVDs) to accelerate the dewatering process (Bergado et al., 1993). In the case of larger deformations, the performance of PVDs can be reduced, which is why a staged application is recommended (Chu et al., 2006). A comprehensive overview of studies related to accelerated consolidation using PVDs can be found in Sakleshpur et al. (2018). The consolidation of soft soil in combination with PVDs can be further accelerated by applying vacuum simultaneously to surcharge loading (Indraratna et al., 2011). Alternative variations to enhance the performance of PVDs with surcharge loading is the application of heat, which effectively increases the hydraulic conductivity (Abuel-Naga et al., 2006), or by using electrically conductive PVDs and applying direct current to take advantage of the effect of electro-osmosis (Chew et al., 2004).

Without the application of surcharging, soft soil undergoes self-weight consolidation and secondary compression only. In the case of deposition of dredged soil or tailings in form of a slurry, settling of particles is a preceding process with a smooth transition to self-weight consolidation. In that case the ground surface is exposed to the atmosphere and soil desiccation occurs due to the removal of water as a consequence of evaporation. In geotechnical engineering, we take advantage of this series of processes when it comes to the question of dewatering slurries in evaporation ponds (Stark et al., 2005a & 2005b) or tailings storage facilities (Shokouhi et al., 2018). There are however restrictions in the effectiveness of evaporation for densifying soil. The evaporation rate, for example, reduces dramatically when the saturation decreases at the ground surface. Depending on the hydromechanical parameters of the soil and the prevailing atmospheric conditions, in terms of temperature, relative humidity, wind speed and radiation, this can lead to variations of the desiccation process leading to a reduced depth of densification due to evaporation (Tang et al., 2010).

The presented contribution introduces a technology named Ventilated Well Method (VWM) that allows the controlled application of evaporation in vertical or horizontal drains inserted in soft soil. In the following, the basic principle is introduced first together with the underlying physics. Experimental small- and large-scale investigations in the laboratory are subsequently presented. The paper finishes with considerations for the practical application and the conclusion.

2 PRINCIPLE & PHYSICAL BACKGROUND

2.1 *Basic principle of the Ventilated Well Method (VWM)*

The underlying idea of the VWM is to induce evaporation where we as geotechnical engineers would like to see it happen, namely in the ground. For this purpose, dry air will be blown into a drainage well, in the case of a vertical installation at the bottom end (Figure 1, left), to induce a continuous flow of air. In order to intensify evaporation, relative humidity can be reduced and temperature increased. However, just for sake of inducing evaporation, it is usually enough to let air circulate within the well at ambient conditions. Alternatively, a heat source could be placed at the bottom end of the well inducing naturally a flow of air upwards and sucking ambient air down the well. Without airflow, the relative humidity would increase to nearly 100% avoiding any evaporation of air. However, with ongoing air circulation, relative humidity is reduced inducing evaporation from the surrounding soil.

A casing with opening secures the well from collapsing, and a geotextile in the form of a fleece avoids fine soil to be transported into the well (Figure 1, right). Naturally, the presence of a geotextile and a casing reduces the actual evaporation of the soil. Furthermore, the influence of soil density on the evaporation process was not studied in detail before. Experiments and numerical simulations have been conducted in the past to quantify the actual evaporation for the special conditions shown in Figure 1. It can also be expected that the relative humidity increases with ongoing evaporation while the air flows along the well. Also, this condition was investigated in detail during the presented study.

At quasi static conditions the flow rate of water leaving the soil around the well equals the actual evaporation rate. The induced water flow consequentially reduces the pore water pressure in the soil surrounding the well creating an increase in effective stress that not only enforces volumetric strain on the soil but also increases the strength right from the beginning of the air circulation due to the induced increase in effective stress.

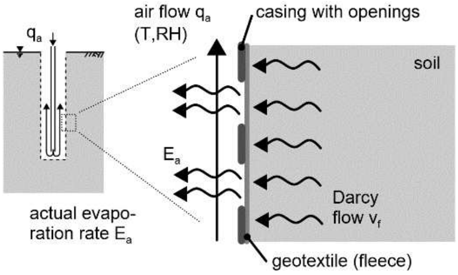

Figure 1. Principle of the Ventilated Well Method (VWM) with overall configuration of a vertical well with air circulation (left) and a close-up view of the conditions at the wall of the well (right).

2.2 *Soil physical parameters*

The physical parameters and processes that underlie and influence the principle of the VWM are summarized in Figure 2. Starting with a water content beyond the liquid limit LL for soft soils, ongoing evaporation will force the water content to reduce in a rate depending on the hydraulic conductivity of the soil at the given void ratio state. This reduction in water content activates suction increasing the effective stress linearly as the soil is fully saturated at this stage (Mishra & Scheuermann, 2021). The soil densifies with increased effective stress and can be assumed to follow the normal consolidation line (Mishra et al., 2021). Ideally, the VWM operates at fully water saturated conditions as the evaporation rate significantly reduces when the saturation starts to drop. The distinct reduction of the saturation happens at the air entry value, which coincides with the shrinkage limit SL of the soil. From thereon, residual shrinkage is significantly reduced. The dotted line in Figure 2 shows this border for the operation of the VWM with the gain in densification, the covered water content range and the activated suction highlighted in grey.

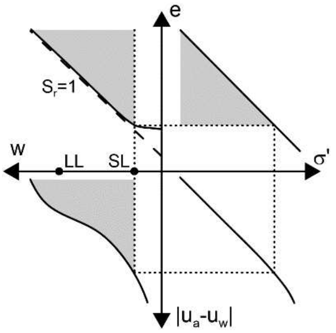

Figure 2. Physical parameters and processes underlying and influencing the principle of the Ventilated Well Method (VWM) with the operation range highlighted in grey.

Numerous investigations have been conducted within the presented study on the shrinkage behavior of various soft soils (Mishra et al., 2020a) and the role of salinity on the soil engineering properties (Mishra et al. 2018b) and shrinkage behavior (Mishra et al., 2019). Experimental procedures based on the evaporative method have been developed to measure the soil water retention in combination with the soil shrinkage curve (Mishra et al., 2021) and the hydraulic conductivity function for the application range of the WVM based on evaporation tests (Mishra et al., 2020b). In these investigations, electromagnetic measurement methods have been extensively used to quantify changes in water content and density (Mishra et al., 2018a & 2020c, Bore et al., 2021).

2.3 *Evaporation rate*

The limiting factor for the application of the VWM is the establishment and preservation of the evaporation rate throughout the dewatering process. Ideally, the evaporation rate should be chosen in a way to maintain a continuous flow of water without forcing an early air entry at the transition from soil to well. An early air entry can for example occur when the applied evaporation rate exceeds the flow rate that can be maintained by the soil. Therefore, one important question that had to be answered was whether porosity changes of a soil during dewatering can influence the evaporation rate. Previous concepts from hydrology assume constant porosity, which is not the case when soil shrinks. The influence of changes in porosity on the evaporation rate has not yet been considered in detail..

In order to answer this question an experimental set-up was developed that allows the implementation of evaporation tests without forcing the soil sample to densify by establishing a continuous water supply through unlimited provision of water and the boundary water head applied at the top surface of the sample (Figure 3). Using a Mariotte's bottle, the water table was held constant at the surface of the soil specimen. The evaporation rate was measured by weighing the Mariotte's bottle while the weight of the soil specimen was observed to quantify any water content changes. With the aim to provide a normalized actual evaporation rate based on the potential evaporation, the weight loss of a cylinder with distilled water was observed simultaneously as well.

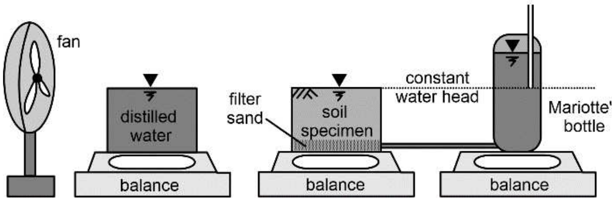

Figure 3. Experimental set-up for quantifying the porosity dependent actual evaporation rate relative to the potential evaporation rate.

The results of this investigation covering porosities from 0.6 to 0.72 including conventional evaporation tests that involved soil shrinkage showed clearly that changes in porosity do not significantly influence evaporation rate. Without the application of wind, the evaporation rate of some soils was even slightly higher than the potential evaporation rate. However, depending on the type of soil and its salinity, the actual evaporation rate can distinctly be reduced compared to the potential evaporation rate. As a result of this study it became clear that the soil type needs to be factored in when the actual evaporation rate is calculated from the potential evaporation rate. However, changes in porosity can justifiably be neglected.

Other factors that have to be considered in calculating the actual evaporation rate within the well are the influence of the geotextile and the reduced surface of the soil in contact with air due to the presence of the casing. In a simplified form, the actual evaporation rate E_a for the VWM can be calculated based on the potential Evaporation rate E_p as:

$$E_a = E_p \cdot f_S \cdot f_G \cdot f_C \quad (1)$$

with reduction factors f_S, f_G and f_C for the influences of soil type, geotextile and casing, respectively. The potential evaporation rate can be estimated with suitable methods (e.g. Hargreaves & Samani, 1982). The reduction factor accounting for the soil type f_S needs to be determined experimentally.

For the correct quantification of the actual evaporation rate based on tests with cylindrical soil samples, a new methodology was developed that on the one hand takes into account soil deformations during the shrinkage process and on the other hand avoids evaporation from the sides (Zhang et al., 2021). For some saline soils and soil wastes the reduction factor f_S can be as low as 0.5. However, for most natural soils f_S is close to 1. The reduction factor considering the effect of geotextiles f_G can vary between 0.5 and 1, for natural soil and thin geotextiles f_G can be assumed to be 1. As the soil type can further influence the performance of the geotextile, consequently influencing this factor, f_G should be tested experimentally as well. Depending on the ratio between opening area and total area of a casing the reduction factor f_C for the influence of a casing linearly varies between 0.15 and 0.4 for opening area ratios of 3% to 12%.

2.4 *Concluding comment on the boundary condition within the well*

Because of the underlying principle of the process, which is based on controlling the relative humidity within the well, one could assume that the suction effect is indirectly controlled with this process. In this case, one could use the well-known Kelvin's equation (Lu & Likos, 2004) to calculate the equivalent total suction from the relative humidity and temperature of the air. However, this total suction would be established at fully equilibrium condition only, when no more water would be removed from the soil. The process of evaporation can here be considered as a transition process ultimately leading to this equilibrium state.

This fact is important in that it dictates how the condition within the well for the VWM is represented in a computational model. While suction would be represented as a hydraulic head or pressure boundary condition, the use of a constant evaporation rate as a flow boundary condition is for representing the condition of the VWM more realistic. Although both boundary conditions will produce qualitatively similar results, the resulting evolution of densification will be overestimated by using suction as the driving force.

3 EXPERIMENTS

3.1 *Small-scaled laboratory experiments*

3.1.1 *Approach & materials*

An extensive parametric study was conducted with a series of small-scaled laboratory experiments involving variations in the most important boundary conditions influencing the processes that underlie the principles of the VWM (Mishra & Scheuermann, 2021). As the aim was to use the dataset for directly upscaling the test results to larger scales, a systematic variation of geometrical boundary conditions in combination with different soil types including variations of the pore water chemistry and of the physical conditions of the circulated air was implemented. Besides of the air temperature, it was also the aim to vary and control the relative humidity what turned out to be more complex than anticipated. Therefore, only air at ambient conditions has been used for this study at various flow rates. A further aim was to provide a data set that can be used for validating computational models for on the one hand simulating the shrinkage of soil due to the application of the VWM, and on the other hand for simulating the evaporation process taking place within the well. Two different soils were used for this study. The central geomaterial for the overall study was dredged soil from the Port of Brisbane (PoB) and kaolin was included as a reference material (Table 1).

Table 1. Consistency limits and coefficient of compressibility of the tested soils.

Soil	Liquid limit	Plastic limit	Shrinkage limit	Coefficient of compressibility
Port of Brisbane	54%	36%	12%	3.32
Kaolin	90%	36%	35%	2.85

In the following, one experiment with variation of the well size is presented in detail. A comprehensive description and analysis of the entire study can be found in (Mishra & Scheuermann, 2021).

3.1.2 *Set-up & implementation*

The experimental set-up was designed in a way to accommodate six cylindrical moulds (Figure 4) in parallel to allow a direct comparison of the test results for one set of samples. The cylindrical moulds with a height of 300 mm and an internal diameter of 142 mm were placed on a balance to continuously observe the loss of weight during the test. Three different sizes of wells were placed in the center of the moulds made of wire mesh enwrapped with geotextile (Table 2 and Figure 5). Ambient air with a relative humidity of 50.9±3.8% and a temperature of 22.1±0.1°C was blown into the well with a constant flow rate of 7 l/min producing laminar flow conditions within the well. As a consequence, the flow velocity of the air in the well changed with changing well size giving the air in larger wells a longer residential time within the well. The mould was closed at the top with a transparent lid to avoid surface evaporation. The lid had a scale attached to it to allow a visual analysis of the shrinkage development. Furthermore, the well was at the top end sealed and connected to the lid opening to ensure that shrinkage is driven by circulated air in the well only. A RH sensor in the opening of the lid allowed measurement of the relative humidity of the outflowing air. Cameras were placed at the top and at the side to visually inspect any deformation of the soil samples throughout the experiment. The moulds have been equipped with conventional tensiometers to observe the evolution of the suction within the soil sample. Unfortunately, due to cavitation of the water in the tensiometers they could not be operated for the complete duration of the test but allowed extrapolation of the further evolution and therefore giving an indication of the suction values reached during the experiment (Figure 6). For this experiment and throughout this study, the soils have been conditioned at an initial water content of 1.1 times the liquid limit (Table 2) ensuring water saturated initial conditions, and the tests were run for a duration of 30 days. Although, shrinkage cracks occurred the soil samples remained saturated after 30 days. Figure 4 presents a schematic of the moulds including the equipment used and Figure 5 shows two moulds in operation.

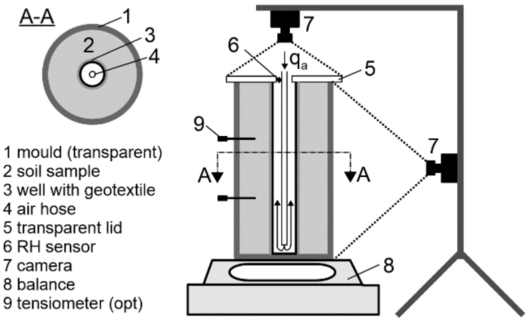

Figure 4. Schematic representation of the moulds used for the study including equipment to observe and measure the condition of the soil and its shrinkage behavior.

Table 2. Soil sample and initial water content w_{init}, varied well sizes, injected relative humidity and observed relative humidity of the outflowing air [adopted from Mishra & Scheuermann 2021].

Sample/w_{init}	Well size (mm)	RH input	RH output
Port of Brisbane 100%	large (60)	50.9±3.8%	55.7±4.7%
	medium (40)		60.5±5.4%
	small (25)		56.2±4.1%
Kaolin 54%	large (60)		63.9±4.2%
	medium (40)		59.9±3.9%
	small (25)		sensor failure

Figure 5. Left: The three different sizes of wells made of wire mesh and geotextiles, and right two moulds filled with Kaolin in operation [adopted from Mishra & Scheuermann 2021]

3.1.3 *Results*

Figure 6 shows the temporal evolution of the measured suction with interpolation using a suitable function over the duration of the test for all sizes of the wells. In case of Kaolin, the well size did not influence the activated suction while for the PoB dredged soil the activated suction increased with increasing well size. The extrapolated evolution of the interpolation function of the measurements should be taken with caution, especially with the large well sizes, where the tensiometers failed relatively early in the test. It should be also noted that the dredged PoB soil is saline (35 g/l), which influences on the one hand the evaporation process and as a consequence also the evolution of the activated suction. On the other hand, the osmotic suction resulting from the salinity contributes to the measurements with the tensiometers. Significant differences for both soils was recognizable only for the large wells, which is probably connected to the fact that both tensiometers used for the kaolin (top and bottom) showed disturbed measurements and failed relatively early in the test. Nevertheless, the extrapolation of the measurements give a good estimation of what suction was approximately prevailing during the experiment.

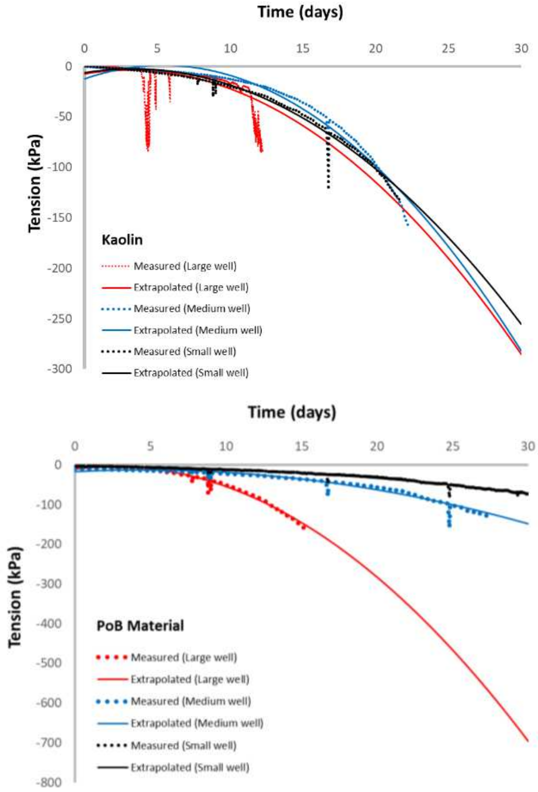

Figure 6. Evolution of suction within the sample measured with the bottom tensiometer including extrapolation for all well sizes (top) for the Kaolin and (bottom) for the Port of Brisbane dredged soil [adopted from Mishra and Scheuermann (2021)].

Figure 7 shows the loss in water content over the duration of the experiment (Mishra and Scheuermann 2021). Since both soils have been conditioned at 1.1 times the liquid limit, the starting water content is different for both soils (Figure 7). As can be seen from Figure 7, there are distinct differences in the evaporation rates for the various well sizes, which is connected to the increased surface area between well and soil over which evaporation occurs. In this connection, one has to keep in mind that the flow rate of air was kept constant consequently leading to different flow velocities of air within the well. The variation of flow rate was part of the study of Mishra & Scheuermann (2021) but is not presented here.

There are also distinct differences in the evaporation rates of both soils. Preliminary evaporation tests with both materials as shown in Figure 3 resulted in a reduction factor for the soil of fs=1, which means that there is no reduction of the potential evaporation rate as a consequence of the soil type. The materials used to build the wells were the same for both soils with a maximal area of the wire mesh over which evaporation can take place. Consequently, no significant reduction of the evaporation rate was to be expected as a result from the design of the well. As the tests discussed here have been conducted at exactly the same relative humidity and temperature conditions for the circulated air, the evaporation rate should have been consequently the same for both materials, which was not the case. The explanation for this lies simply in the fact that for both tests, the evaporation test of Figure 3 and the VWM experiments of Figures 4 and 5, have been conducted with different batches of dredged soil. This observation highlights the importance of conducting evaporation tests as described in Zhang et al. (2021) as part of a characterization exercise for every soil that will be treated with the VWM.

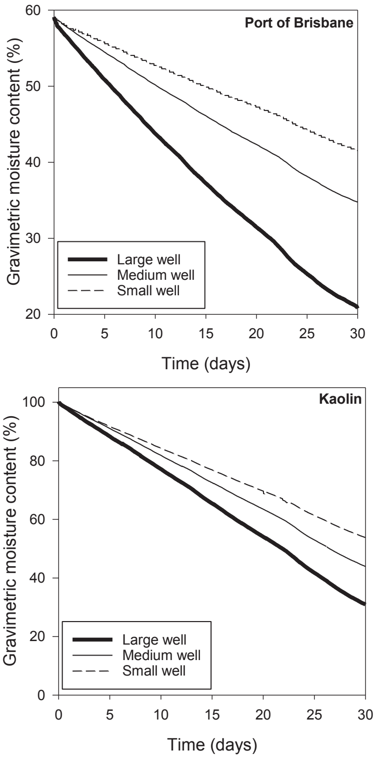

Figure 7. Water loss over time for the Kaolin and PoB samples during the experiments [adopted from Mishra and Scheuermann (2021)].

A very encouraging result of this experiment is that the evaporation rates of all tests have been nearly constant throughout the entire duration of the experiment, which confirms the observations of the formerly discussed evaporation tests according to Figure 3 that changes in the porosity or density, respectively, do not influence the evaporation rate (see Figures 7 and 8). This observation also confirms that for this set of experiments the samples remained saturated over the complete duration of the experiment. While Kaolin with a gravimetric water content of w=31% for the large well was already slightly beyond the shrinkage limit after 30 days of evaporative dewatering the PoB dredged soil samples were still far away from this stage (w=21% for the large well).

The changes in density for all samples over the duration of the test (30 days) are shown in Figure 8. The changes in dry density do not show the linear evolution like the water content (Figure 7), which is connected to the uncertainties with the image analysis using the pictures made with the cameras and the markers connected to the mould and the lid (Figure 4). With the appearance of cracks, the visually analyzed volume change underestimates the real density changes. A slightly larger change in density can be expected based on the linearity of mass-volume relationship in 100% saturated condition of the material. Nevertheless, both graphs of Figure 8 show clearly a significant increase in density as a result of the applied evaporative dewatering. Also note that with increasing well size the gain in dry density over the same period of time increases as well signifying the higher degree of dewatering for larger wells as shown in Figure 7.

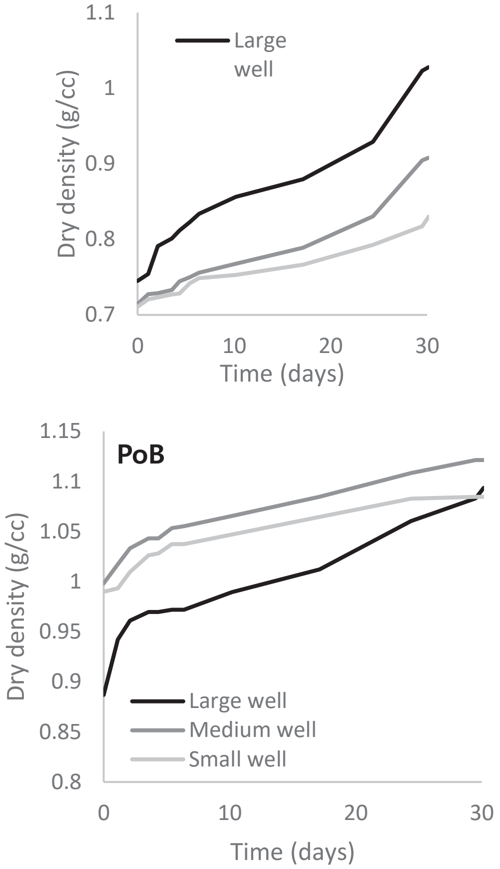

Figure 8. Density change over time for the PoB and Kaolin samples during the tests [based on data from Mishra and Scheuermann (2021)].

3.2 *Large-scaled laboratory experiments*

Large-scale laboratory experiments have been implemented with PoB dredged soil to support the upscaling of the outcomes of the study presented before and for testing the group effect of several wells operated simultaneously in combination (Figure 9). For testing the VWM on a larger scale, three water barrels with a sample height of 60 cm and a diameter of 40 cm have been used in combination with the same well diameters. Surface deformation and weight have been observed during this test, and samples have been taken after the experiment to test water content/density and the shear strength using vane shear tests. All test have been conducted with the same flow rate of 7 l/min. For testing the group effect of wells, a circular tub with 0.5 m height and 1.5 m diameter was filled with a gravel at the base and PoB soil separated with a geotextile. A commercial circular PVD has been used as a well for this experiment. In sequential steps, wells have been activated with a constant flow rate of 7 l/min, and deformations of the surface have been observed using cameras. After completing the tests samples have been taken for further analysis. The results of these experiments are currently analyzed and will be reported in a subsequent publication.

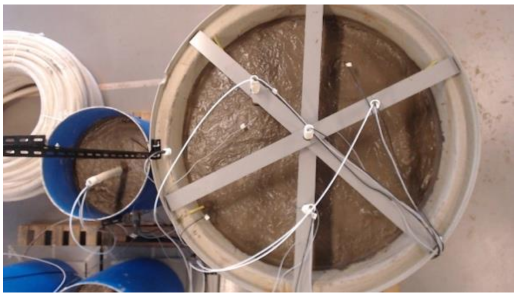

Figure 9. Large-scale VWM experiment in water barrels (left in blue) with varying well diameter and circular tub for investigating the group effect of wells used for the VWM (right).

3.3 *Field experiments*

An important aspect of the overall study was to test the VWM under field conditions. For this purpose, with strong support of one of the industry partners of the project, circular Prefabricated Vertical Drains (PVDs) have been installed in a grid with two different distances down to a depth of 11m. Cone Penetration Tests (CPT) have been conducted before the installation, and it was scheduled to repeat them after completion of the test. Unfortunately, it was not possible to complete this experiment with a final CPT test. As it turned out, there was a highly hydraulically conductive layer of seashell connected to a nearby river, which caused continuous flooding of the wells. Nonetheless, this test provided the opportunity to gain important experiences about a practical application of the VWM. A new field experiment is currently in planning and will be implemented at the beginning of 2022.

Figure 10. Installation of conventional circular PVDs at a field site for testing the VWM (left), and installed drains in a grid of seven drains.

5 PRACTICAL IMPLICATION & CONCLUSIONS

The laboratory experiments conducted within the project have clearly shown the potential of the VWM as an alternative solution for consolidating and dewatering soft soils. It became apparent that the efficiency of the method is strongly connected to the actual evaporation applied within the well, which is why a detailed study was conducted only on this topic. A simplified approach was developed to quantify the actual evaporation to be expected within a well depending on the soil type to be dewatered and the conditions of the used well.

For the practical application of the method, there are still some open questions to be addressed especially within another field experiment. For example, the potential precipitation of salt within the well as a consequence of ongoing evaporation. So far, this was not considered, but also not observed, within the study. Another aspect is how to handle the initial drainage or emptying of the well before starting the operation of the VWM with injecting air.

All in all, the investigations conducted within the project have clearly shown that the VWM is a viable alternative for dewatering soft soil. It will be the objective of future investigations to, on the one hand, prove and improve the efficiency of the method, and on the other hand to make this technology ready for use for practical applications.

6 ACKNOWLEDGEMENTS

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