Secondary settlement of dikes in peat areas based on CPTu.

Area of interest at location Mijdrecht,by Jos Teeuw, Waternet

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Preface

This bachelor thesis is the final part of my bachelor degree in Civil Engineering at Delft University of Technology. I have made this research at the department of Geosciences & Engineering commissioned by the waterboard Waternet.

I would like to thank Geert in ‘t Veld and Jos Teeuw for their help and data from Waternet and in addition I would like to thank Cor Zwanenburg for his supervision and help with this thesis from the university.

Joost Dick
Delft, 19 June 2020

Abstract

This study aims for a software tool that predict secondary settlements in soft layers on which secondary dikes are founded based on cone penetration test data. In the literature study five equations have been found that relate cone resistance and friction ratio to volumetric weight and over consolidation ratio. With the volumetric weight and over consolidation ratio the NEN-Bjerrum settlement parameters can be determined and with that the strain for a layer. After this study the focus lies on developing a software tool and the resulting output. In the end it seems, qualitatively, that the results are not useful in engineering practise because the resulting settlements are unexpectedly large.

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Introduction

The defence against water is in the Netherlands one of the biggest challenges of all times. Innovating as the Dutch are they have built an enormous collection of dikes. These dikes can be divided in primary and secondary dikes. The secondary dikes protect the polders from floating while the primary dikes are the sea dikes and those surrounding rivers and lakes. Most of these secondary dikes are built in peat rich areas in the west of the Netherlands. The properties of these soft layers result in secondary settlements, also known as creep. Therefor it is necessary to run this study on the secondary settlement of soft layers underneath the secondary dikes in the Netherlands to predict the settlements for good periodic maintenance.

The waterboard of the region Amsterdam, Waternet, came up with the question if it is possible to make a software tool to predict these secondary settlements based on cone penetration test (CPT) data. Together with the TU Delft this study tries to find a direct relation between CPT data and settlements and develop a software tool to predict them.

This will be done in two steps, first of all a literature study on the relations is run to come up with a method that links CPT data to settlements. This is done by looking at the following questions:

- What methods are there to predict settlements?
- What parameters are involved in these methods?
- How to determine the parameter values with a CPT?

All together this must answer the question:

- Is it possible to predict settlements based on CPT data?

These questions must give a good starting position for the second part of the study, the development of a software tool that can predict the secondary settlement of secondary dikes in peat areas with CPTu data. This will be discussed in chapter 2. A workplan for the software tool is presented in this chapter and the results from the software tool can be found in chapter 3. From these results a conclusion on whether it is possible to develop a software tool to predict secondary settlements can be found in chapter 4.

1. Background theory

In this chapter the theory necessary for a creep settlement prediction model will be discussed. First of all an overview of some different methods and later the different parameters will be handled.

1.1 Different methods for settlement prediction

To get a better view on what model to use in a later stage of the project this part will give an overview of what different methods have been used in the past and which are still used.

Already in the 1930's the first settlement models were made. One of the first known and used methods is the one of Keverling Buisman. In his model there are two parts. The first one indicates a settlement that happens immediately and a term that is affected by the influence of time. Based on this relation of Buisman, Koppejan expanded this formula so it became dependent of stress and soil parameters where Buismans formula was still very limited. It can be seen that Buismans formula uses two parameters, αp and αs and as it is a settlement prediction these parameters should have a dimension of length. It was the first method that distinguishes between primary and secondary settlement. Both formulas are given in equations 1.1 and 1.2. The formula of Koppejan is throughout the years very commonly used in engineering practise in the Netherlands. The Koppejan formula uses a logarithmic relation between the stress and strain this is based on the compression law of Terzaghi. Another point of interest of the Koppejan method is that unloading and reloading will not be accurately be calculated.

$$(1.1)\ \ z_t = \alpha_p + \ \alpha_s \log(t)\ \ (\text{Haan}, 2007)$$

$$(1.2)\ \ \varepsilon = \frac{1}{C_p}\ln\left(\frac{\sigma_v'}{\sigma'_0}\right) + \frac{1}{C_s}\ln\left(\frac{\sigma_v'}{\sigma'_0}\right)\log(t)\ \ (\text{Haan}, 2007)$$

Where in the Netherlands Koppejan is commonly used, Bjerrum is used in the rest of the world for settlement of soft layers. The main difference between these two methods is that the Koppejan uses a primary and secondary strain predict whereas Bjerrum uses three for its calculations. The first part of the equation is the strain due to preloading conditions, the second part is due to loading and the third part is the time depend part of the strain, this can be seen in equation 1.3.

$$(1.3)\ \ \varepsilon = RRlog\left(\frac{\sigma_p'}{\sigma_0'}\right) + CRlog\left(\frac{\sigma_f'}{\sigma_p'}\right) + C_\alpha \log\left(\frac{t - t_n + \theta_n}{t_{ref}}\right)\ (\text{Visschedijk}, 2010)$$

Another difference between the Koppejan and the Bjerrum method is there approach of the creep. The method of Koppejan uses a log(t) relation while the Bjerrum method also uses creep rate which indicates with that velocity the creep will occur due to the stress of the soil on top.

These methods are just three of the many settlement prediction models but highlighted as they are commonly used in the past and the Bjerrum method forms the basis for the new a,b,c-isotach model which is even more accurate for big strains than the Bjerrum model (Sipkema, 2006). The method of Koppejan could be seen as a asymptotic settlement model because over a very long period of time the settlement will converge to a asymptote of strain. That is due to the secondary settlement which is super positioned to the primary settlement. As can be seen in figure 1.1. The secondary settlement of Koppejan shows a straight line on the semi-logarithmic scale which implies an asymptotic behaviour. Next to this asymptotic model there are timelinemodels and the Bjerrum method is one of those. The big difference between these two models is that the timeline model of Bjerrum assumes that there is a constant strain rate in time due to the stress that is applied. Therefor the secondary settlement is a function of time and stress that will follow one of the timelines. Such a timeline is reached through the amount of applied stress and the time that has been expired to reach it. In later models the influence of time to reach this state is called the equivalent time and is the base for the time dependent part of the formula. This line indicates the velocity for an equivalent time of one day while in practice this can vary widely therefor there are multiple of these timelines as illustrated in figure 1.2.

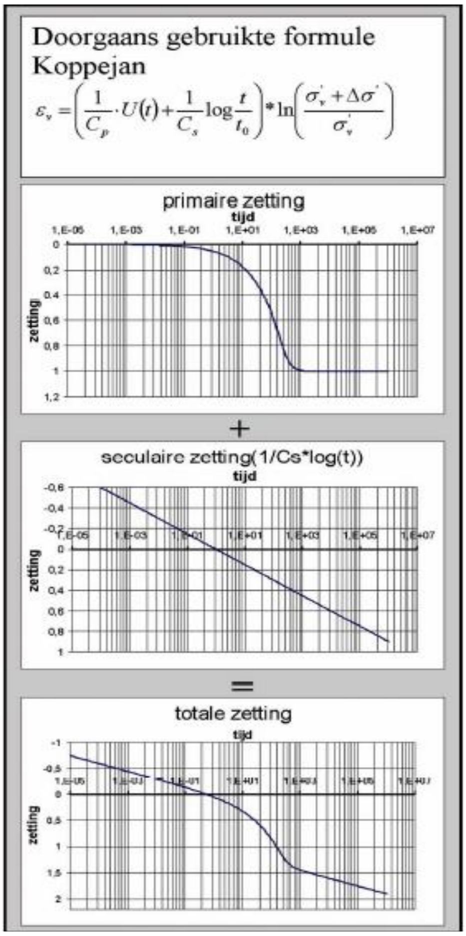


Figure 1.1 settlement graphs of the Koppejan model (Sipkema, 2006)

From these different timelines it is a small step to the a,b,c-isotach model. Since the Bjerrum model is already an isotach model these two do not differ that much. The reason the a,b,c-isotach model is highlighted is because it is one of the newest methods to determine settlements. One of the differences is the approach of the strain, the a,b,c-isotach model uses natural strain whereas Bjerrum uses linear strain, this results in better predictions when there is a lot of loading and de-loading. This is the field with the biggest errors in the Bjerrum method (Sipkema, 2006). Since this is not the case for this study the NEN-Bjerrum method will be leading.

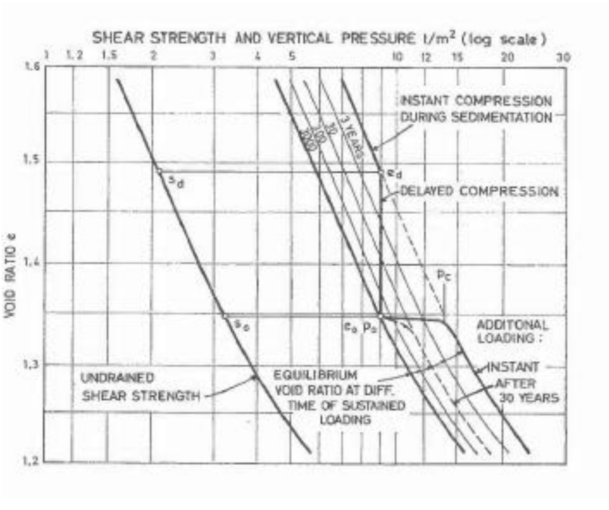


Figure 1.2 different timelines of the Bjerrum-method (Haan, 2007)

1.2 Parameters that influences the settlement

The models discussed in the previous chapter are based on parameters which will be discussed over here. "*New settlement models as good as they are, their calculations will never be better than the parameters used.*" ~ (den Haan, van Essen, Visschedijk, & Maccabiani, 2003)

The easiest way to get the parameters for either Koppejan or the Bjerrum method is by extracting them from the graphs that display settlement, or change in void ratio, against the stress. For the last parameter for the Bjerrum method C_α the settlement must be plotted against time.

As it can be seen in figure 1.3, Koppejan has four soil parameters that influences the strain. These Cp, C'p, Cs and C's. In figure 1.3 a plot of the strain is shown with these parameters. In this graph there are two parts to take in account. The first part is where the stress level is lower than the yield stress while the second region is beyond this point. In this graph one can see 4 lines that represent settlements of either 1 day or 10 days. From these lines the parameters can be determined. The common way to get these graphs is by performing oedometer tests. That makes the formula of Koppejan only dependent of stress and time. Since, for this study, the stress does not vary anymore and the relation between present stress and the applied stress is the over consolidation ratio (OCR). Which makes the settlement only dependent on time and not on the stress path. Figure 1.4 gives just like 1.3 an overview of strain against stress but a determination of the parameters for the NEN-Bjerrum method is shown next to the Koppejan method..

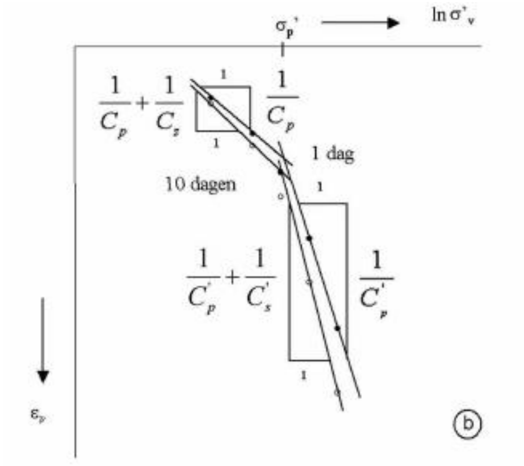


Figure 1.3 Settlement plot of Koppejan (Sipkema, 2006)

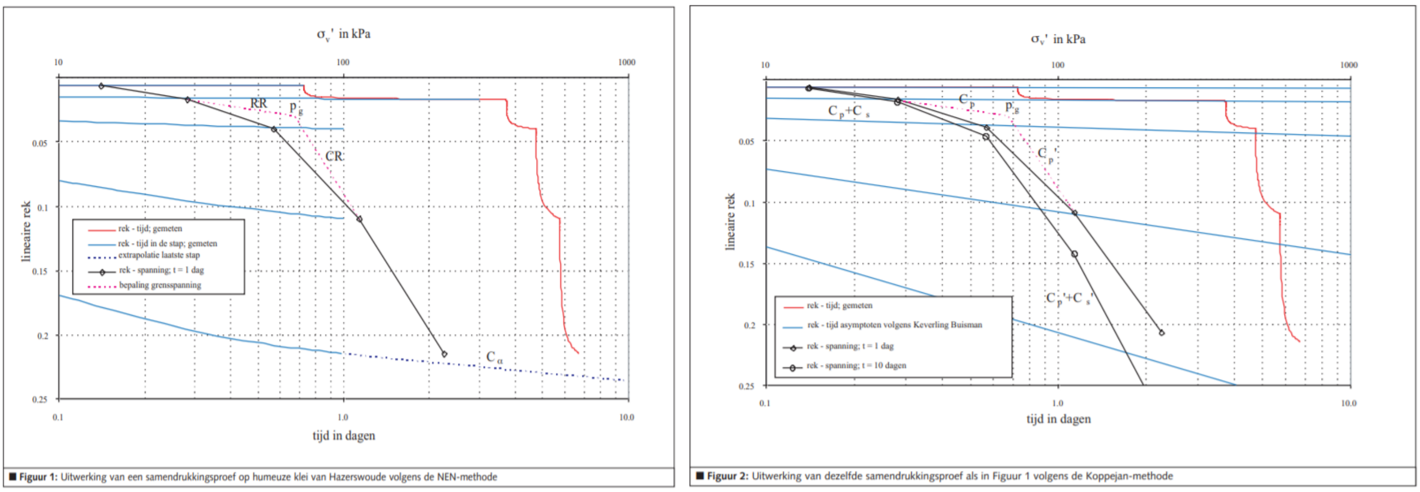


Figure 1.4 Settlement parameters. Left with Bjerrum method and right with the Koppejan method. (den Haan, van Essen, Visschedijk, & Maccabiani, 2003)

As can be seen in figure 1.4, the first two parameters of the NEN-Bjerrum method are determined by taking the slope of the graph. In many cases like in figure 1.4 there will be some transition stage close to the yield stress value. So the stress paths are extrapolated and that gives the right slopes for the RR and CR. From the formula of Bjerrum the only parameter left is the Cα which is the value for the creep. In figure 1.4 there is an extrapolation of the settlement vs. time graph (the blue lines) and the slope from this gives the Cα value. When a settlement vs log(time) diagram is given, the graph will have a S-curve like in figure 1.5. From such a graph it is therefore possible to get three slopes which result in the three parameters CR, RR and Cα.

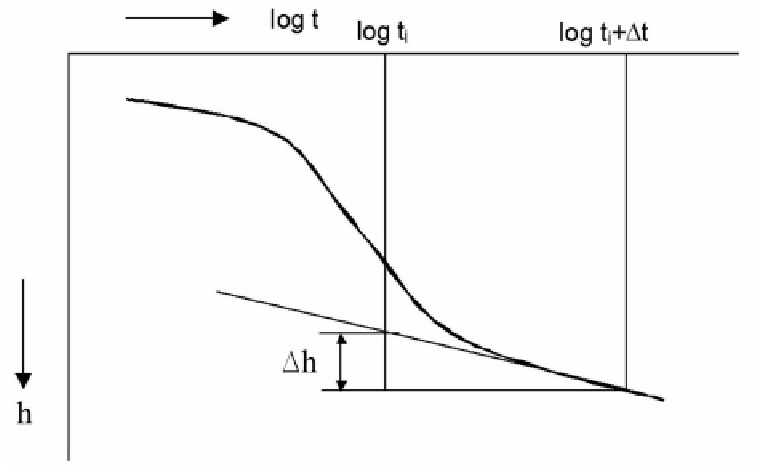


Figure 1.5 Settlement over time graph (Sipkema, 2006)

Having a look at the a,b,c-isotach model there are similar relations. First of all the settlement must be natural strain instead of linear strain, this is because natural strain uses a finite thickness of the sample while for linear strain a settlement bigger than the original thickness theoretical can be reached something which is physically impossible, this is because the parameters change due to settlement but the original parameter set is used for the total calculation. Then there exist a line of direct strain due to the loading. The slope of this line gives the first parameter, the a. Once the yield stress has exceeded it will follow a line with a constant strain rate, the slope from these lines give the second parameter, the b. Finally the parameter of the creep, the c, which is based on the distance between two of isotachen, the lines with equal strain rate but with a different equivalent time. This parameter is also determined in the same way Cα of the NEN-Bjerrum method. Plotting the strain against time and determine the slope. Every following isotach has a ten times multiplier of the previous isotach. With this relation there is a constant distance between two isotachen and the vertical distance at the same stress is then equal to c times the natural logarithm of 10. As can be seen figure 1.6.

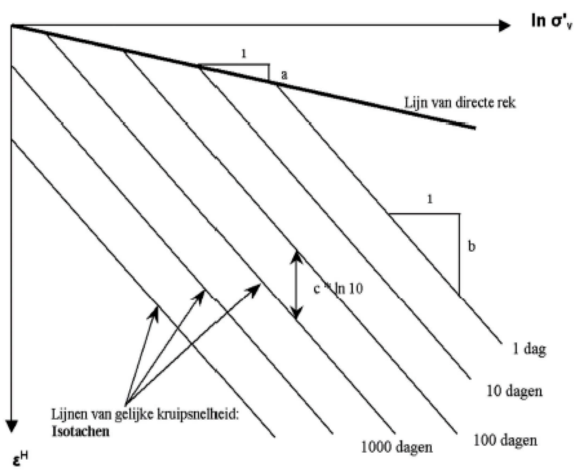


Figure 1 Parameter determination of the a,b,c-isotach model (Sipkema, 2006)

1.3 Parameter values

As already mentioned in paragraph 1.2, the parameters that occur for the methods are most likely determined by oedometer tests. These tests result in stress vs settlement or time vs settlement graphs. For these tests, samples of the soil must be collected and analysed in a laboratory.

Next to the soil parameters the stress parameter is one of importance, as mentioned before for the long term settlement the stresses will be considered as constant and it is about the ratio between the applied stress and the present stress also known as the OCR. For this it is necessary to know how the soil profile looks like. A rough indication can be done through the cone penetration test (CPT). With a CPT a standardized cone will penetrate the soil and measure the resistance against the cone and the friction it will have sliding through it, the friction ratio. Together these two result in soil type characteristics namely the cone resistance qc [MPa] and the friction ratio [%]. With these numbers an estimation of the soil profile can be made and from literature the specifics weights can be used to calculate the stress in every layer.

A direct way to calculate the OCR from a CPT is given by Mayne and Kemper. They have run over 100 samples to find an empirical relationship between the net cone resistance and the overburden stress. The relation that has been found is can be seen in equation 1.4.

$$(1.4)\ \ OCR = k_c\left(\frac{q_c - \gamma * z}{{\sigma_{v0}}'}\right)\ \text{(Mayne \& Kemper, 1988)}$$

They found out that the value of k_c will lie between 0.3 and 0.8 for an electric cone while for mechanical cones it has to be between 0.12 and 0.5. The remark they make is that to have a good value for the k_c a oedometer test should still be applied.

New research has made it possible to relate the settlement parameters to CPT data. This has been done by combining two studies. The first study relates unit weight of soil to CPT data (Lengkeek, de Greef, & Joosten, 2018). The second study relates unit weight of the soil directly to the parameters that influence the settlement (Bierma, 2019). Combining these two studies makes it possible to directly relate CPT data to settlement parameters. This could lead to prediction of settlement without doing any adjacent oedometer tests. From the first study it can be found that the relation between CPT data and the saturated volumetric weight is given by the equation by equation 1.5. After comparing 300 test samples with this new formula and the results from oedometer tests the parameters are determined. An overview of the test results and the parameters can be seen in figure 1.7. The remark here must be made that there is an approximate error of about 1 kN/m^3 this can be explained by the very low values for soft and organic soils and the biases in oedometer tests and the CPT tests itself.

$$(1.5)\ \ \gamma_{sat}(q_t; R_f) = \gamma_{sat;ref} - \beta * \log\left(\frac{\left(\frac{q_{t;ref}}{q_t}\right)}{\left(\frac{R_{f;ref}}{R_f}\right)}\right)\ \text{(Lengkeek, de Greef, \& Joosten, 2018)}$$

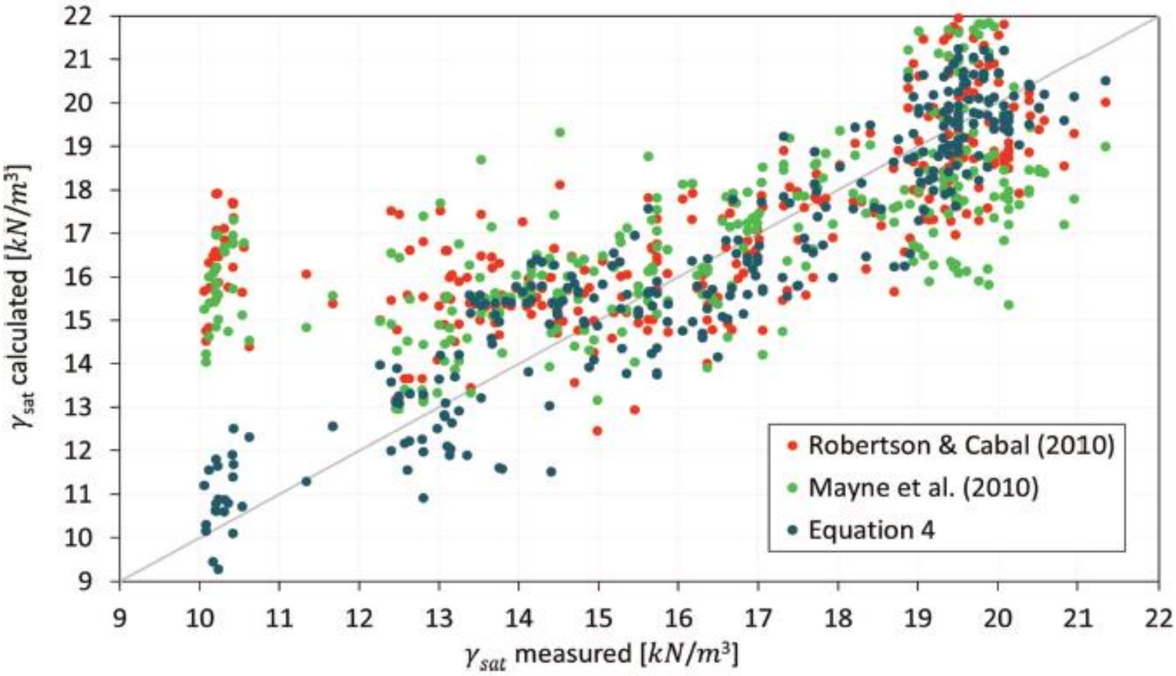


Table 3. Proposed parameters for Equation 4.

Parameter	Adopted best fit values
$\gamma_{sat,ref}$	19.0
$q_{t,ref}$	5.0
$R_{f,ref}$	30.0
β	4.12

Figure 1.7 Estimation of the volumetric weights compared to measured values and the parameters that fit the equation of figure 10 (Lengkeek, de Greef, & Joosten, 2018).

The second study which provide an relation between the settlement parameters and the unit weights can now be used to relate CPT data to settlement parameters. Bierma has done several data analyses on the settlement parameters compared to the ratio between dry volumetric weight, saturated volumetric weight, the water content and the volumetric weight of water. An overview of the relations that Bierma found can be seen in figure 1.8. This table does not only show the parameters for the NEN-Bjerrum but method but also for the a,b,c,-isotach model and the ratios between parameters. Since Lengkeek et al. provides a relation between the saturated volumetric weight and the CPT results the first column of the table is of most interest.

Table 5.1: Overview of all the equations from the best regression models.

	γ_{sat}/γ_w	γ_{dry}/γ_w	W
RR	$0.4266 \cdot e^{-1.9727x}$	$0.0831 \cdot e^{-1.7323x}$	$0.0249 \cdot x^{0.5148}$
CR	$2.1636 \cdot e^{-1.5148x}$	$0.6062 \cdot e^{-1.2197x}$	$0.2692 + 0.1309\ln(x)$
C_α	$0.2798 \cdot e^{-2.0386x}$	$0.0510 \cdot e^{-1.7212x}$	$0.0176 + 0.0117\ln(x)$
CR/RR	$5.5333 + 4.1742x$	$9.5946 + 2.4506x$	$12.8100 - 0.5449x$
CR/C_α	$-12.9153 + 24.9377x$	$8.7312 + 18.0940x$	$21.5298 \cdot x^{-0.3849}$
a	$0.3035 \cdot e^{-2.1731x}$	$0.0525 \cdot e^{-2.1091x}$	$0.0128 \cdot x^{0.5948}$
b	$1.7470 \cdot e^{-1.7342x}$	$0.4150 \cdot e^{-1.4663x}$	$0.1634 + 0.0927\ln(x)$
c	$0.2135 \cdot e^{-2.1974x}$	$0.0350 \cdot e^{-1.9637x}$	$0.0109 + 0.0082\ln(x)$
b/a	$7.2308 + 3.7129x$	$10.8766 + 2.1366x$	$13.8725 - 0.5554x$
b/c	$-9.5669 + 21.9827x$	$9.5274 + 15.9516x$	$21.0302 \cdot x^{-0.3449}$

Figure 2 The relations between volumetric weights and settlement parameters (Bierma, 2019).

1.4 Theory conclusion

After the research done on the theory of settlement and methods to come up with the parameters of the settlement predictive models this chapter will give a brief summary of this study which will be a cradle for the next step of this project, the development of the software.

For the method of settlement there has been three methods. The Koppejan method which is widely used throughout the field in the Netherlands but it is very restricted. The two isotachmodels which provide better insight of settlements in which the a,b,c-isotachmodel gives a better prediction for large settlements over time than the NEN-Bjerrum method. Those two methods are actually very similar and because the NEN-Bjerrum method is used more often in engineering practise and because big strains are not expected, this method will be the base for the software that is going to be developed.

$$(1.3)\ \ \varepsilon = RRlog\left(\frac{\sigma_p'}{\sigma_0'}\right) + CRlog\left(\frac{\sigma_f'}{\sigma_p'}\right) + C_\alpha \log\left(\frac{t - t_n + \theta_n}{t_{ref}}\right)\ \text{(Visschedijk, 2010)}$$

As for this study there must be a prediction of the secondary settlement and the elastic behaviour of the settlement is therefore not of interest. This makes that equation 1.3 should be rewritten and the first part should be left out which result in a time and stress dependent equation of the creep which is stated as in equation 1.6.

$$(1.6)\ \ \varepsilon_{creep} = C_\alpha * \log\left(\left(\frac{1}{OCR}\right)^{\frac{CR-RR}{C_\alpha}} + \frac{t}{t_{ref}}\right)$$

In this new stated formula the creep strain is a function of parameters that can all be determined by CPT data. The relations that are necessary to do so are listed below in resp. equations 1.4, 1.5, 1.7, 1.8 and 1.9 . This makes that for every soil layer the strain can be determined and with the strain and the initial thickness the settlement.

$$(1.4)\ \ OCR = k_c\left(\frac{q_c - \gamma * z}{\sigma_{v0}{'}}\right)$$

$$(1.5)\ \ \gamma_{sat}(q_t; R_f) = \gamma_{sat;ref} - \beta * \log\left(\frac{\left(\frac{q_{t;ref}}{q_t}\right)}{\left(\frac{R_{f;ref}}{R_f}\right)}\right)$$

$$(1.7)\ \ RR(\gamma_{sat}) = 0.4266 * \exp\left(-1.972 * \frac{\gamma_{sat}}{\gamma_w}\right)$$

$$(1.8)\ \ CR(\gamma_{sat}) = 2.1636 * \exp\left(-1.5148 * \frac{\gamma_{sat}}{\gamma_w}\right)$$

$$(1.9)\ \ C_\alpha(\gamma_{sat}) = 0.2789 * \exp\left(-2.0386 * \frac{\gamma_{sat}}{\gamma_w}\right)$$

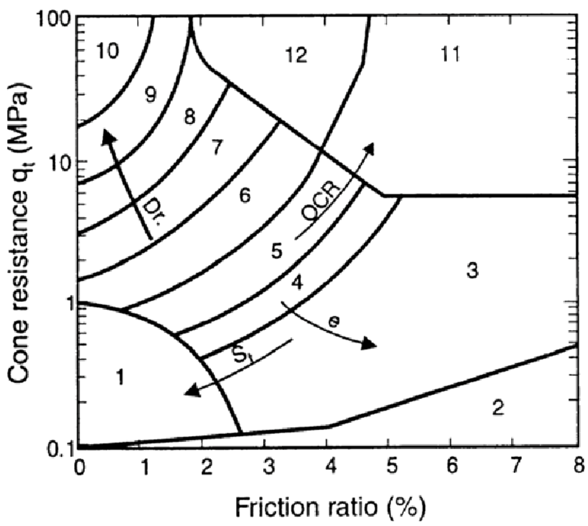
These 5 equations should be enough to predict the creep settlement of soft and organic soils based on CPT data.

2. Methodology

In this chapter the procedure of the settlement prediction and the workmap for the software tool will be explained. The details about the code itself can be found in appendix C and will not be discussed in this chapter.

2.1 Parameter calculations

For the prediction of the settlement the equations found in chapter one must be linked to one another and linked to different layers as every soil layer has its own properties. The first step in the settlement prediction is the determination of the layers from a CPT file. This is done manually by making distinction in the cone resistance and/or the friction ratio. This creates a layered soil profile with the necessary properties: qc (cone resistance), the Rf (friction ratio) and the thickness of the layer. Next to these qualitative properties each layer has given a soil name to make it better readable in a later stage. This is done according to the Robbertson graph which can be seen in figure 2.1.



Zone	*Soil Behavior Type*
1	*Sensitive fine grained*
2	*Organic material*
3	*Clay*
4	*Silty Clay to clay*
5	*Clayey silt to silty clay*
6	*Sandy silt to clayey silt*
7	*Silty sand to sandy silt*
8	*Sand to silty sand*
9	*Sand*
10	*Gravelly sand to sand*
11	*Very stiff fine grained**
12	*Sand to clayey sand**

** Overconsolidated or cemented*

Figure 2.1 Soil behavior type graph (Robbertson, 2010)

These results are saved in a comma separated values file to later on read in the code. This is done for several CPT's that have been made available by Waternet. With the CPT data stored, the equations from chapter one can be used to calculate the specific weights for every layer. This is a direct relation between the CPT data and specific weights and is therefore the first calculated step in the tool. With this value the three parameters for the settlement, C_α, CR and RR are calculated. This is also done directly for every layer which is the second calculation step within the tool. The last property that is required for the settlement prediction is the over consolidation ratio. This is the third step but requires some additional steps. Since the OCR is not just a property based on the layer itself but also of the weight above and therefor a function of the depth. For every layer the soil weight it produces, the thickness of the layer multiplied by the volumetric weight of it, had to be calculated and stored as a layer property. For then the OCR is calculated with equation 1.4. With these calculations all the necessary parameters are determined for the strain calculation. This is done per layer and with this strain per layer the settlement of a layer can be determined over time. The summation of all the layers give an indication of the total settlement of the soil profile.

The steps necessary to perform are listed below:

1. Analyse the CPT file and determine the layers
2. Calculate the γ_{sat} per layer
3. Calculate the C_α, CR and RR per layer
4. Calculate the weight per layer and the cumulative weight on top of a layer
5. Calculate the OCR value
6. Calculate the strain per layer
7. Calculate the settlement per layer
8. Calculate the total settlement

2.2 Output

With all these calculations a visualization will be made in the form of several plots, those will be presented in chapter 3 where the results will be.

The first output the tool gives, is an overview of the created soil profile. This is done so one can check if it is correct according to the CPT and if not, one can change it in the CSV file. It is also shown so one will have an understanding of the graphs and where the different layers are located as they are in descending order starting at the ground level. One of the plots that is made is the OCR over depth. This is done because the OCR directly relates to the strain velocity. Another plot that is made to visualize the results is the strain over time per layer. Since in the end the settlement is of interest also a plot of settlement per layer is created and the final plot is the total settlement of the soil layer.

3. Results

In this chapter several plots as explained in chapter 2 will be shown and discussed. These are the outputs of the developed software tool. Two CPT files have been used for these results. They can be found in the appendices. First a location overview will be shown then the determination and finally the created plots.

3.1 CPT P04-30

The first part of the results is of the CPT with number P04-30. This one is made in 2012 by Waternet, figure 3.1 gives an overview of the location. It can be seen that the CPT has been made near a channel near Mijdrecht.

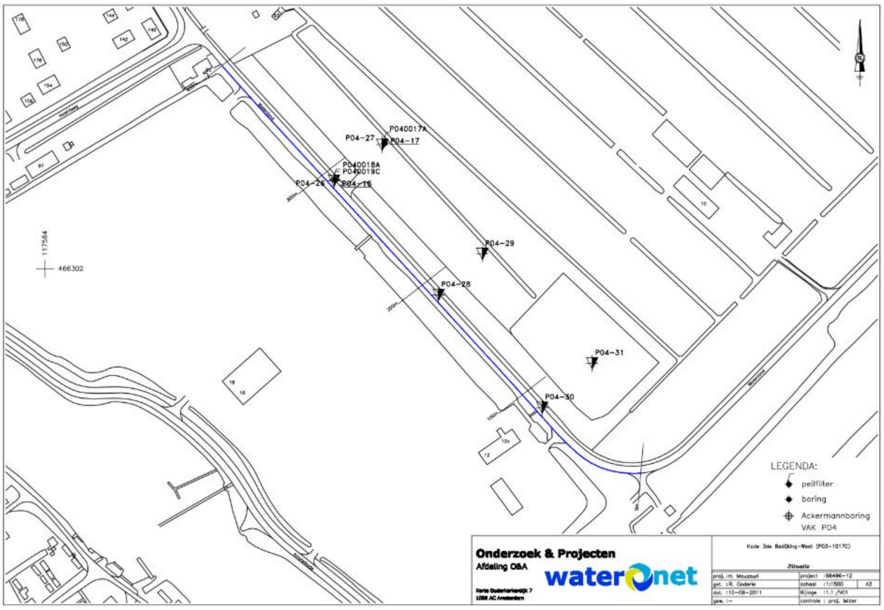


Figure 3.1 Location of the CPT P04-30 (obtained by Waternet, Jos Teeuw)

Some addition information was given by waternet about the conditions before the CPT. The top layer is a path of asphalt followed by a sand layer and a mixture of peat and clay, the last part of the 2 meter boring contains sand and gravel. The CPT graph with the cone resistance and friction ratio can be found in appendix A. Below one can find the determination of the layers according to this CPT graph.

Table 3.1 results of CPT at location P04-30 (CPT graph can be found in the appendix)

Name	qc	Rf	thickness
Veen	0.3	8	2.5
Veen	0.1	2	3
Klei	0.5	7	1
Zand	12	0.8	6

From these results the following plots are made for strain, settlement and also the over consolidation rates. These can be found in figures 3.2 – 3.5.

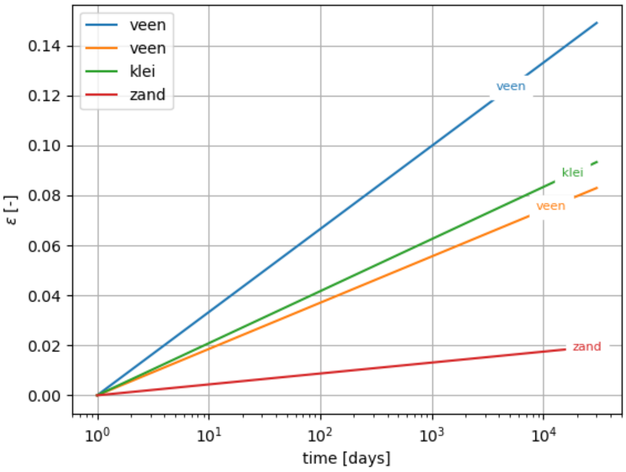


Figure 3.2 Strain over time

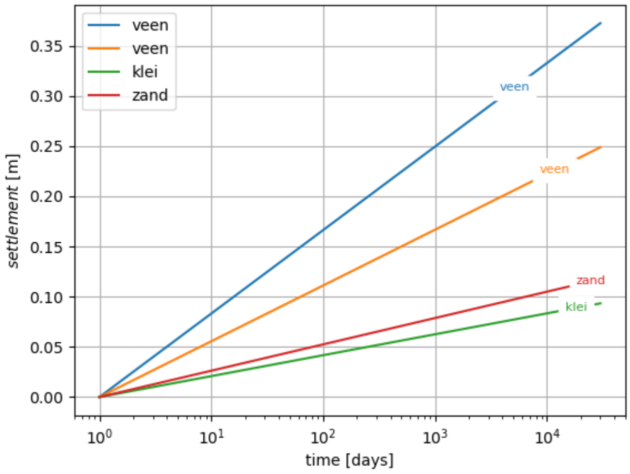


Figure 3.3 Settlement per layer over time

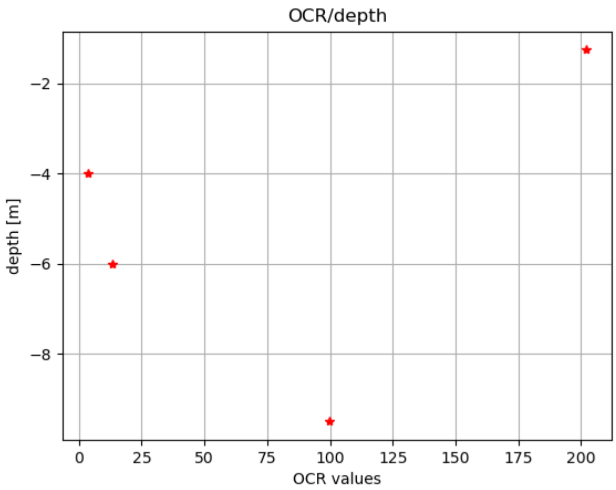


Figure 3.4 OCR values over depth, based on the layers

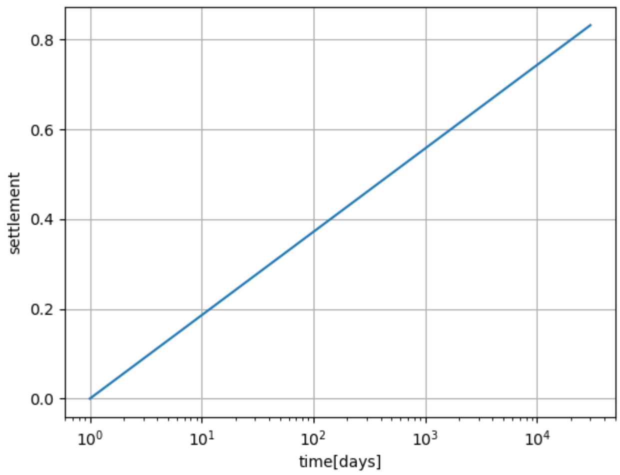


Figure 3.5 Total settlement for the soil profile of P04-30

What can be seen in these graphs is qualitative that the strains and settlements for soft layers (peat and clay) are higher than for sands. This is also what was expected but both seem too high. Next to the strains and settlements, the over consolidation ratios are also expected lower. Even though this should reduce the strain rate and therefor the total settlement this is not clearly visible in the graphs. One of the reasons that the OCR of the first layer is high could be because, as mentioned in chapter 1, the cone resistance is reduced by the overburden and divided by the effective stress of this overburden soil. For a top layer there is almost no overburden. Still this layer has the highest strain and settlement.

3.2 CPT E09-532

This CPT is made in 2017 by Waternet at the location of the new IJburg centrumeiland to give an advise for founding a new pumping station. The location of this CPT is shown in figure 3.6 and shows that this one is close to the IJmeer.

Figure 3.6 Locations of the CPT's for Centrumeiland IJburg (in 't Veld, Centrumeiland IJburg (onderheid transportriool), 2017)

Waternet also gave a soil profile for these CPT's and for the CPT E09-532 this profile is build up as followed: topsand layer than varying thin sand, clay and peat layers until a depth of 10 meters. Followed by sand layers than about 10 meters of loam and clay layers and at the bottom there is a thick sand layer. This does not completely overlap with the determination found by the Robbertson classification graph in chapter 2. The soil profile determined for the software can be found in table 3.2. The corresponding plots can be found in figures 3.7 - 3.10.

Table 2 Results of CPT at location E09-532 (CPT graph can be found in the appendix)

Name	qc	rf	thickness
zand1	11	0.5	1.5
zand2	16	0.8	3.2
klei1	1.5	3	0.6
silt1	7	0.8	0.8
silt2	3	2	0.5
klei2	1	4	0.5
zand3	6	1.2	0.2
silt3	1.5	1.5	1.5
silt4	1	2	1
klei3	1	3	0.5
silt5	1	2	1.2
klei4	1.5	4	0.7
zand4	12	1	2.8
silt6	8	2.5	2.5
zand5	8	1.5	1
silt7	3	3	4
silt8	2	3	3.6
zand6	7	1	1.2
zand7	30	1	2

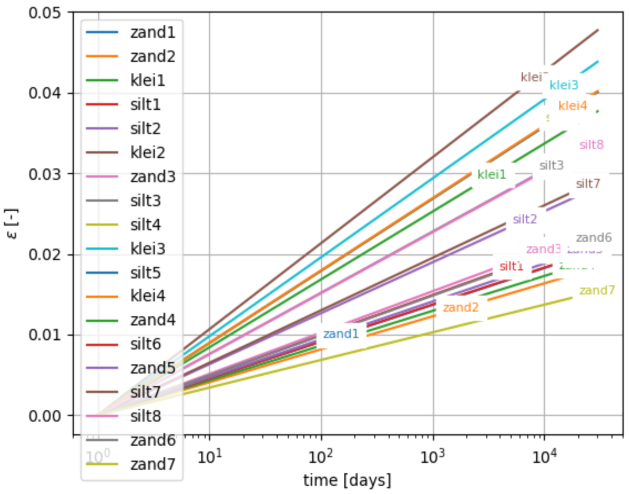


Figure 3.7 Strain per layer over time

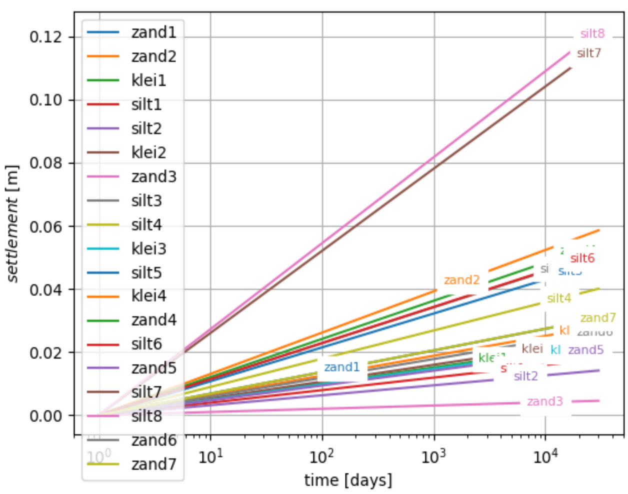


Figure 3.8 Settlement per layer over time

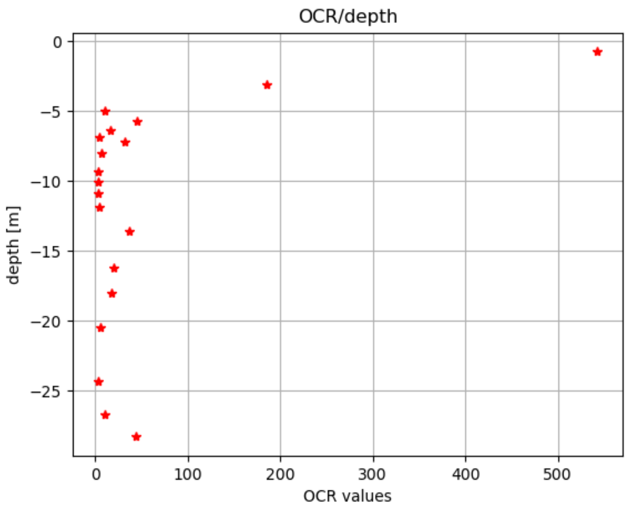


Figure 3.9 OCR over depth

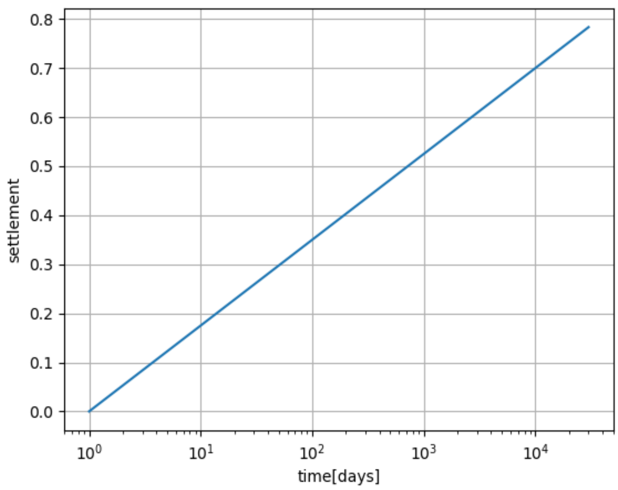


Figure 3.10 Total settlement for the soil profile of E09-532

First of all, just like in the CPT P04-30, the values of the OCR are in general very high as can be seen in figure 3.9. In figure 3.7 the strains of soft layers are again higher than for sandy layers as would be expected. The strains that are found per layer are smaller than in the previous CPT and so are the settlement per layer. An explanation for the two layers that reach higher settlements, silt 7 and 8, is that these two layers also have a greater thickness. These two layers are classified as clay by Waternet so greater settlements are again expected. For the total settlement one can see that this is still high which in this case is also due to a deeper soil profile than CPT P04-30.

4. Conclusion

This chapter concludes the report on secondary settlements based on CPT data. With answering the question whether it is possible to build a software tool to predict the creep based on CPT data.

First of all it was required to find relations that could link these two directly to each other. As can be found in chapter 1, there is a relation that can be used to transform CPT data into volumetric weight and according to the research of Bierma this volumetric weight can be used to predict the settlement parameters CR, RR and C_{α}. To get the creep settlement, these three parameters and the over consolidation ratio is required for each layer. For the over consolidation ratio there has also been found a direct relation with the cone resistance, the overburden pressure and an empirical constant. These relations make it possible to directly relate the CPT to the strain and therefor to the settlement.

The next part of the project was to develop a software tool to predict these settlements. Linking the different layers and determine the parameters for each layer. It turned out that this was also possible with the steps explained in chapter 2. The results of the software are found in chapter 3 and they show that even though it is possible to link all the data and the different layers the strains are in the expected order of magnitude but the settlements are not. Especially looking at the total settlement this is too high. A creep settlement of about 80 cm is not an expected order of magnitude. One of the reasons for this phenomenon is that sand and silt layers are also taken into account. While these layers are not expected to have any creep behaviour.

To conclude the project, the settlements that are predicted based on CPT data is not reliable to work with in engineering practice when looking at the results in chapter 3. Improvement has to be done on layer selection, some quantitative research on the error margins and random samples should be used to verify the calculated strain and settlements.

References

Bierma, S. J. (2019). *Assessment for upper and lower limits for parameters obtained from constant rate of strain oedometer tests.* Delft.

Deltares. (2016, februari 9). Embankment design and soil settlement predictions. *D-Settlement manual*. Delft.

den Haan, E., van Essen, H., Visschedijk, M., & Maccabiani, J. (2003). ISOTACHENMODELLEN: Help, hoe kom ik aan mijn parameters? *Geotechniek*, 62-69.

Duinen, A. v. (2014). *Handreiking voor het bepalen van schuifsterkte parameters.* Deltares.

Haan, E. D. (2007, april). Historische achtergrond bij het isotachenmodel. *Historische achtergrond bij het isotachenmodel*.

in 't Veld, G. J. (2017). *Centrumeiland IJburg (onderheid transportriool).* Amsterdam: Waternet.

Lengkeek, A., de Greef, J., & Joosten, S. (2018). CPT based unit weight estimation extended to soft organic soils and peat. *Cone Penetration Testing 2018* (pp. 389-394). Delft: CRC Press.

Mayne, P. W., & Kemper, J. B. (1988). Profiling OCR in Stiff Clays by CPT and SPT. *Geotechnical Testing Journal*, 139-147.

Nachanok, C. (2017). Methods fo evaluating overconsolidation ratio from piezocone sounding results. *Underground Space*, 182-194.

Robbertson, P. K. (2010). *Soil behaviour type from the CPT: an update .*

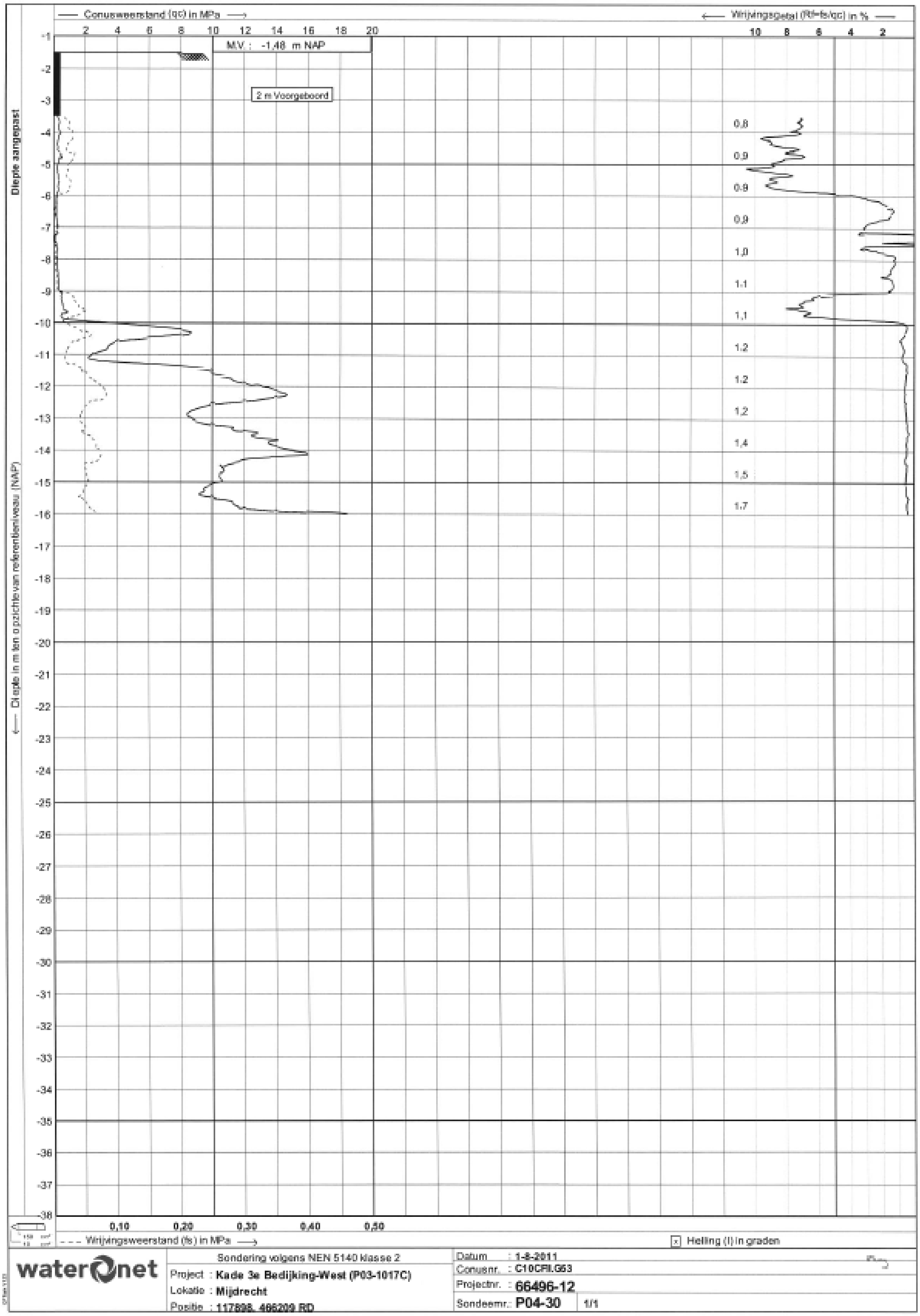
Sipkema, D. (2006). *a,b,c-isotachenmodel van a,b,c tot zetting.* Delft.

Visschedijk, M. (2010). Isotachen berekeningen op een sigarendoosje. *Geotechniek*, 30-33.

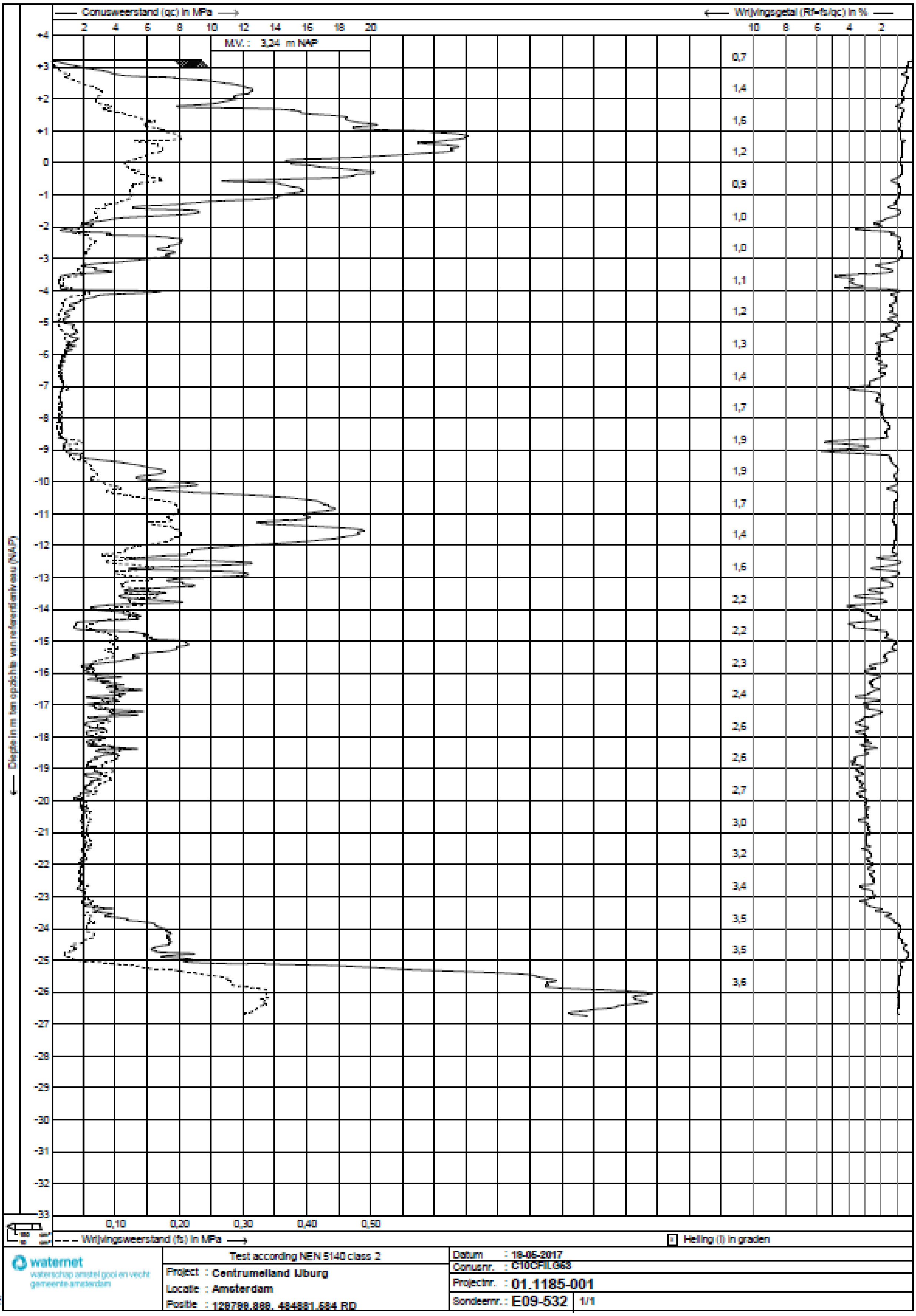
Wroth, C. (1984). The interpretation of in situ soil tests. *Géotechnique*, 449-489.

Appendices

Appendix A: CPT P04-30



Appendix B: CPT E09-532



Appendix C: Software code

See next page.