PILOT PROJECT: RSDYK2008

STRENGTH OF PEAT DYKES EVALUATED BY REMOTE SENSING

GEBIEDSDEKKENDE DIJKSTERKTE BEPALING MET REMOTE SENSING

PROGRAM FLOOD CONTROL 2015

15 DECEMBER 2008

SUMMARY

In the context of the FloodControl 2015 project this pilot project RSDYK2008 is done to establish the possible correlations between terrestrial remote sensing techniques, geological information of the surrounding subsurface, geophysical details of a dyke and the quality of peat dykes. The pilot project was done at three sites in Reeuwijk, The Netherlands.

Spatial and temporal variations in the radiation temperatures measured by remote sensing have been established at all sites. These thermal responses of the dykes are mainly related to the seasonal variation and to the distribution in the moisture content of the topsoil. The thermal images acquired during the dry period (August) show a positive relationship with the images of October and a negative relation with the images of December. The multi-temporal near infrared images of the same sites do not show any obvious relationship.

The subsurface geology and stratigraphic profile have been obtained from interpolated pseudo-sections of the 2-D and 3D electrical imaging surveys and from boreholes and Dutch Penetration testing (CPT). The lateral and vertical variations as well as the heterogeneity of the dyke material is very obvious and a clear relation between resistivity imaging and boreholes and CPT testing is established.

Soil moisture is one of the most important parameter affecting surface stability in soil structures. This is because in peat soil, the effective stresses and shear strength are directly related to water content, and even pre-failure deformations are largely controlled by the moisture content. Since the distribution of water content and total unit weight vary in both vertical and horizontal layer in the peat units in the dykes.

The problems as “kwel” and possibly subsidence in the “problem” dyke site Tempeldijk-South are identified by nearly all investigation methods, however, it is often only by knowing from another investigation method that the problem could be pinpointed.

Main conclusions of this pilot project are:

- The comparison of the reference site (Tempeldijk-North) with Tempeldijk-South (a known “problem” location) shows that in all surface and subsurface investigations the Tempeldijk-South surface and subsurface structure are more irregular which are due to or indicate “problems’ such as “kwel” and subsidence.
- The thermal infrared images of Tempeldijk-South showed a layered structure which is reflecting the subsurface structure of the dyke. The layered structure was detectible likely because excess water was present in some of the layers.
- Visual images showed differences in vegetation cover at locations where excess water is likely present.
- The gamma ray survey shows a pattern that is likely related to the real subsurface structure.
- The data from the Algemeen Hoogtebestand Nederland may show patterns indicating deficiencies in a dyke.

Recommendations

Thermal infrared in combination with near infrared imaging and in particular hyper spectral imaging should be able to accurately locate problem areas in dykes. The near-infrared or hyper-spectral imaging will likely be a supporting tool to be used to compensate the thermal infrared interpretation for vegetation, and environment and climate changes. The hyper-spectral method could not be fully evaluated but is possibly a better means for investigation than near-infrared. A combination with Lidar data would probably be adventurous, even the data of the Algemeen Hoogtebestand Nederland may already give sufficient accurate data for dyke investigations. It is recommended that the ideas developed in this pilot project are fully worked out and investigated in detail to develop a

methodology that will be able to detect dyke deficiencies more efficiently, accurately, and cheaper than possible by visual inspection only.

KEY WORDS

Key words: dyke, peat, thermal, infrared, radiation, reflectance, resistivity, Reeuwijk, RSDYK

LIST OF ACRONYMS

ADC	Agricultural digital camera
NAP	National mean sea level reference
NIR	Near infrared
TIR	Thermal infrared
TAW	Technical Advisory Board for Water Barriers

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1 INTRODUCTION

1.1 Flood Control 2015

Dykes are a flooding protection mechanism in the Netherlands and some other counties. According to Van Baars (2005), the primary (3200km) and secondary (14000km) dykes in the Netherlands protect more than 50% of the country from flooding. To maintain the groundwater level and drain the precipitation of the lower lands, water is pumped from the ditches to the canals and from the canals into the sea. Many of the secondary dykes are so-called “peat dykes”. These dykes consist of peat that has not been excavated while the surrounding peat was excavated. The peat was excavated for fuel starting from the early middle ages.

The peat and clay dykes act as a flooding tempering means in case a large flooding of the Western part of the Netherlands occurs. The flooding is unlikely to be stopped by these dykes but the lowering of the flooding rate may give opportunities to use dykes and the roads that are often on top.

Due to the shear large number of dyke length it is impossible to do a thorough investigation over the full length. Presently the quality of the dykes is established by visual inspection and only at locations where the quality is visually deemed to be low; a further investigation to the quality of the dyke is done. Apart from the fact that a visual inspection is slow and may be biased and subjective, a more important problem is that a dyke may in different seasons behave qualitative differently, even on different days depending on the weather. The visual inspection is generally restricted to a once a year or may be a couple of times more in case the safety of the dyke is not trusted, but certainly not on a basis that can ascertain that a dyke is stable in all environmental conditions.

Remote sensing from the air allows for a far faster means of inspection. However, although it has been thought for a long time that remote sensing may be an attractive option it has never been systematically studied. Therefore this pilot project has been initiated to establish whether remote sensing is a possible option for dyke quality assessment before and during flooding situations.

Within the context of the Flood Control 2015 project (FC2015 project) the secondary peat dykes have a specific function. Secondary dykes may reduce the flooding rate in the Westen part of the Netherlands when the main dykes against the sea and main rivers have failed. Important is then how long these dykes may still be able to function. Obviously in a time of a major flooding in the Western part of the Netherlands no time will be available to start an investigation to the quality of the dykes. The quality of the dykes has therefore to be established beforehand.

1.2 Remote sensing

Any vegetation present around the dykes is likely to be influenced by changes in groundwater table or moisture content of the material and vice versa. The health of the vegetation can be affected as the groundwater table becomes too shallow or too deep. The most likely changes are expected to occur in the chlorophyll concentrations in the vegetation which are an indicator of the health state (Van der Meijde et al., 2004). Adams (Adams et al., 1999) showed that in stressed vegetation the absorption efficiency of the chlorophyll decreases and the IR reflectance decreases due to changes in the cell structure of the plant. This leads to a reduction in reflectance in the IR simultaneous with an increase in reflectance in the red.

The spatial distribution of surface temperature around the dyke can be related to the moisture content of the soil. The temperature variation in the subsurface depends on its thermal diffusivity which itself is also a function of water content. The effective soil water content is maximal at the beginning of the spring and then decreases until the end of summer (Behaegel et al., 2006). Soil thermal properties are strongly influenced by the soil volumetric water content, volume fraction of solids and volume fraction of air.

Hence, if the stability of peat and to a certain extend also clay dykes depend on the moisture content, and the health of the vegetation on a dyke is dependent on the moisture content, and it is possible to establish the health of the vegetation by remote sensing, it should then be possible to establish a relation between remotely sensed images and the quality of the peat and probably clay dykes. In the context of the FloodControl 2015 project this pilot project is done to establish the possible correlations between terrestrial remote sensing techniques, geological information of the surrounding subsurface, geophysical details of a dyke and the quality of peat dykes. The pilot project was done at three sites in Reeuwijk, The Netherlands.

1.3 Pilot project objectives

The main objective of this pilot project is to indicate possible relationships between terrestrial remote sensing, geological information of the surrounding subsurface, and weak areas in dykes mainly consisting of peat. Geophysics, boreholes and Dutch Cone Penetration (CPT) tests have been done to investigate the subsurface of the dyke.

1.3.1 SPECIFIC OBJECTIVES

The project addresses the following specific objectives:

- Identify the spatial and temporal variations of the thermal radiation of the dyke materials as well as reflectance features of the grass using thermal infrared (TIR) and near infrared (NIR).
- Determine the variation in the composition of a dyke, the soil moisture condition and the material properties using two and three-dimensional (2D and 3D) electrical imaging surveys, boreholes and CPTs.
- Indicate possible relationships between the thermal infrared, near infrared, and visual remote sensing and the subsurface model of the dyke and possible weak areas of the dyke.

1.4 Research methodology

This pilot project comprises pre-field, field data collection and post field data analysis works. A literature review has been made on terrestrial remote sensing techniques (TIR and NIR) and physical parameters of peat dykes such as moisture content, permeability, porosity, bulk density, organic content and consolidation. Information about the geological setting of the study area also gathered from previous works of different researchers who worked in the study area.

During the field data collection, field images of TIR, NIR and visual were acquired using ground based sensors in three dyke sites. This was done in three different season’s summer, autumn and winter. In addition, 2-D and 3D electrical imaging surveys were conducted on two dyke sites. In the summer boreholes and Dutch cone penetration tests were done for referencing the geophysical subsurface model.

Figure 1-1 shows a summarized schematic workflow that has been used to achieve the objectives of the project.

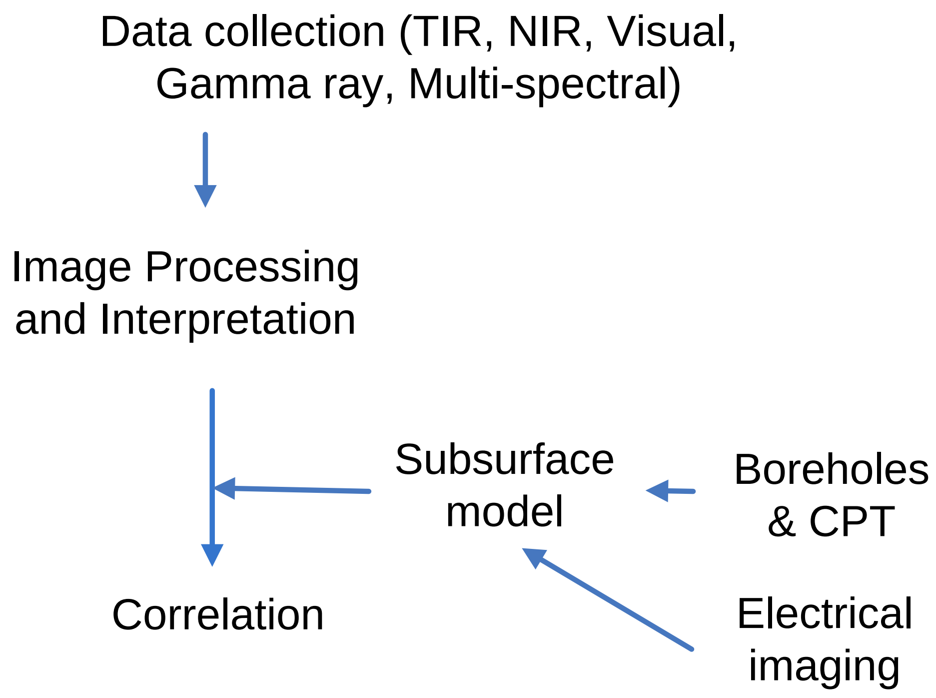

Figure 1-1: Schematic work flow diagram.

1.5 Project partners

The partners in the project and the persons involved in the project are listed in Appendix A.

1.6 Activities

The activities during the project are listed in Appendix B.

2 LIRETURTURE REVIEW

A brief literature review is incorporated in appendix C. The literature review gives an overview of the characteristics of peat and remote sensing characteristics of peat and vegetation as commonly found on dykes. The conclusions of the literature review are many but can be summarized as follows:

- Remote sensing should give good opportunities to evaluate the homogeneity of the surface cover of dykes during various seasons,
- the surface cover is coupled by the presence of water to the deeper materials in the dyke,
- the presence of water is often a good indicator of the possible problems with a dyke, such as excess water (“kwel”), unwanted water flows, or may indicate a situation that the dyke is jeopardized by a shortage of water, e.g. the materials in the dyke are dried out (for example, the “Wilnes” case),
- surface deviations of the dyke are easily detected, and
- remote sensing is a far faster method of investigation of dykes than traditional visual investigations.

3 TEST SITES

3.1 Locations

Reeuwijk is located in a polder area in the province of Zuid Holland, in the central western part of The Netherlands. Maps and aerial photographs of the area and locations of the test sites are included in appendix D. In the area extensive excavation of peat has taken place since the early Middle Ages. Three test sites were selected (Figure 3-1). In this report describing the results of a pilot project, only the test site with problems, "Tempeldijk-South", is fully evaluated.

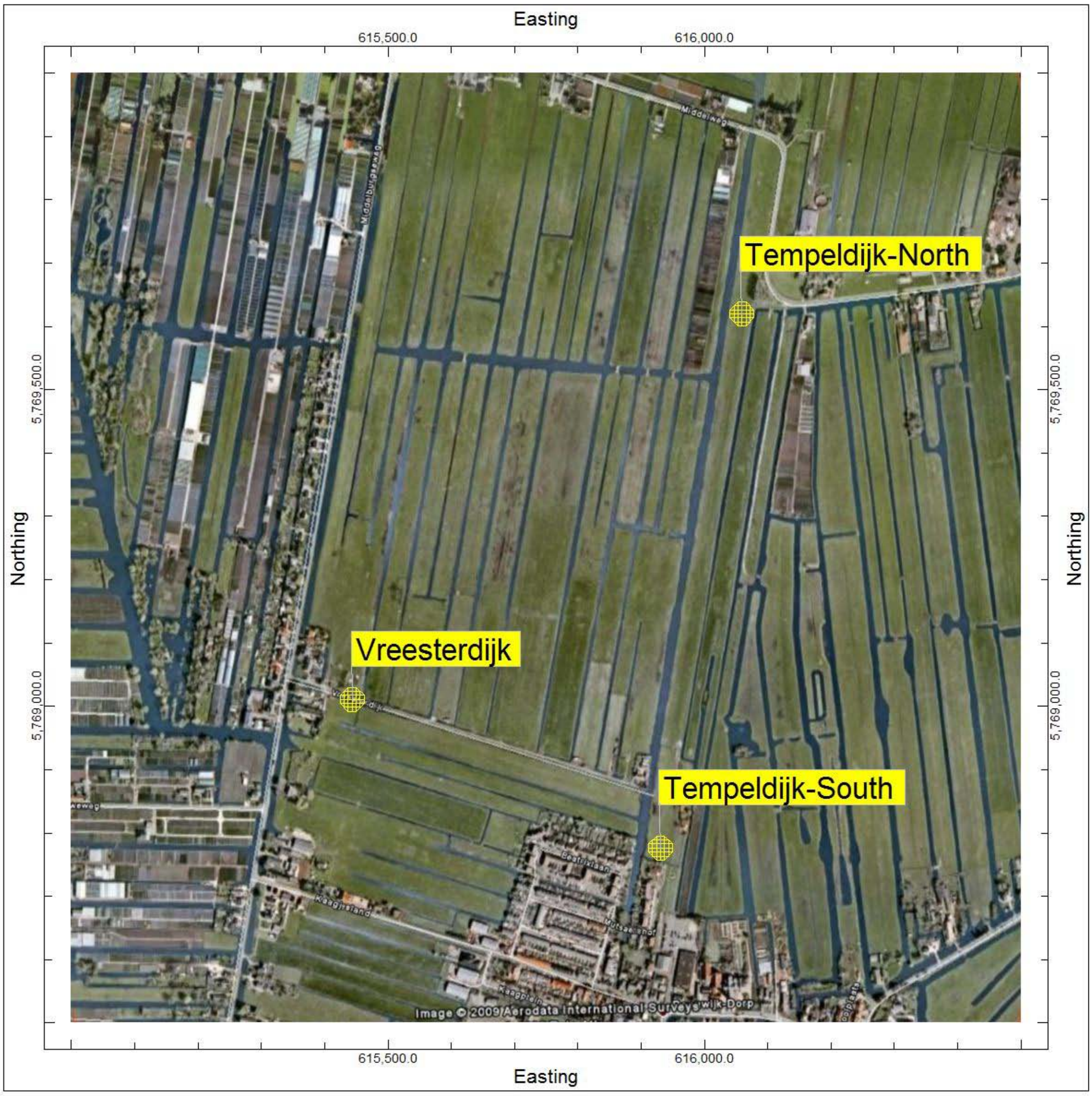

Figure 3-1. Location test sides. The urban area in the bottom middle is Reeuwijk-Dorp. (photo Google Earth, 2008. Grid: UTM (WGS84, zone 31 NH)

3.1.1 VREESTERDIJK

The Vreesterdijk is located in the area where peat has been excavated and consists of a road on an embankment of non-excavated peat. The structure of the dyke is not known in detail, but is assumed to consist of in-situ peat in the lower part. Likely, the dyke has been covered by road pavement materials many times (probably for hundreds of years) and is covered by a bitumen layer at present. The extent in depth of the layers is unknown. The dyke does not function as boundary for a water canal, but as a local division dyke (dam) in the excavated area, and as an access road to a farm.

3.1.2 TEMPELDIJK

The Tempeldijk is the boundary between a high-laying in-situ peat deposit area where the peat has not been excavated and a low-laying area where the peat layer has been excavated. The dyke functions as a dyke (e.g. dam – "boezem kade") for a de-watering canal. Two test sites were selected; one on both ends, e.g. Tempeldijk-North and Tempeldijk-South (originally these were named Tempeldijk-1 and Tempeldijk-2. As this caused confusion names have changed to the more location specific names of Tempeldijk-North and Tempeldijk-South).

3.1.3 TEMPELDIJK-NORTH

Tempeldijk-North location is chosen as reference. The dyke seems to function without known problems. Also on the surface of the dyke no features have been distinguished that may indicate seepage ('kwel'), subsidence', or otherwise features that could be an indication of "problems".

3.1.4 TEMPELDIJK-SOUTH

Tempeldijk-South location is reported to have problems due to seepage ("kwel") and possibly subsidence. For a more detailed description of Tempeldijk-South is referred to chapter 4.

3.2 Geological environment and topography

Geologically the study area is a deltaic environment. The area is rather flat with an average elevation of –1.6 m NAP (National Mean Sea-Level Reference) with man-made dykes and cannels. Polders resulting from reclamation after peat extraction have elevations around –5.0 m N.A.P.

3.3 Climate

According to Köppen's classification, The Netherlands has a moderate sea climate with rain almost throughout the whole year. In general, the winters are mild having an average mean temperature of 1.7^{o} C. The mean temperature may be below zero in the coldest month. In summer five months have a mean temperature over 10^{o} C with a maximum temperature of 17^{o} C in July. The precipitation is evenly distributed over the year with a yearly average of 760 mm (Ten Cate, 1982). In Spring precipitation is low which causes a deficit in surface water due to evaporation.

3.4 Geological setting

The information about the geological setting of the test sites is summarized from previous works of researchers who worked in the area, from regional studies, and from the general geological history of the Netherlands. A summary is included in appendix E. The geological lithology of the area resulted from sedimentation in the Holocene period. During the Holocene, the area was located in the perimarine zone, where the deposits were formed under the influence of sea level fluctuations and sea level rising from the west interacting with river input from the east. This resulted in extensive areas where for a longer time stagnant water and swamps allowed the development of large and thick peat layers. Occasionally marine or river influence caused the deposition of clay and sand layers and lenses.

4 TEMPELDIJK-SOUTH LOCATION

4.1 Introduction

The test site location Tempeldijk-South measures about 100 by 50 m along the Tempeldijk (Figure 4-1). The test location is the west site of the dyke. The top of the dyke is at about -2 m while the bottom of the dyke is at about -5 m. The area is covered with grass that is regularly cut in summer. The first layer of material to a depth of around 0.3 m is a man-made cover of clay with peat (oral information, Rupke, 2008, and confirmed by boreholes). In the canal and at the foot of the dyke at the western site of the dyke “kwel” occurs. Possible a part of the dyke has (slightly) subsided as indicated by the elevation contour lines between p1 and ph1 (Figure 4-1). The elevations are based on the data of the “Actueel Hoogtebestand Nederland”.

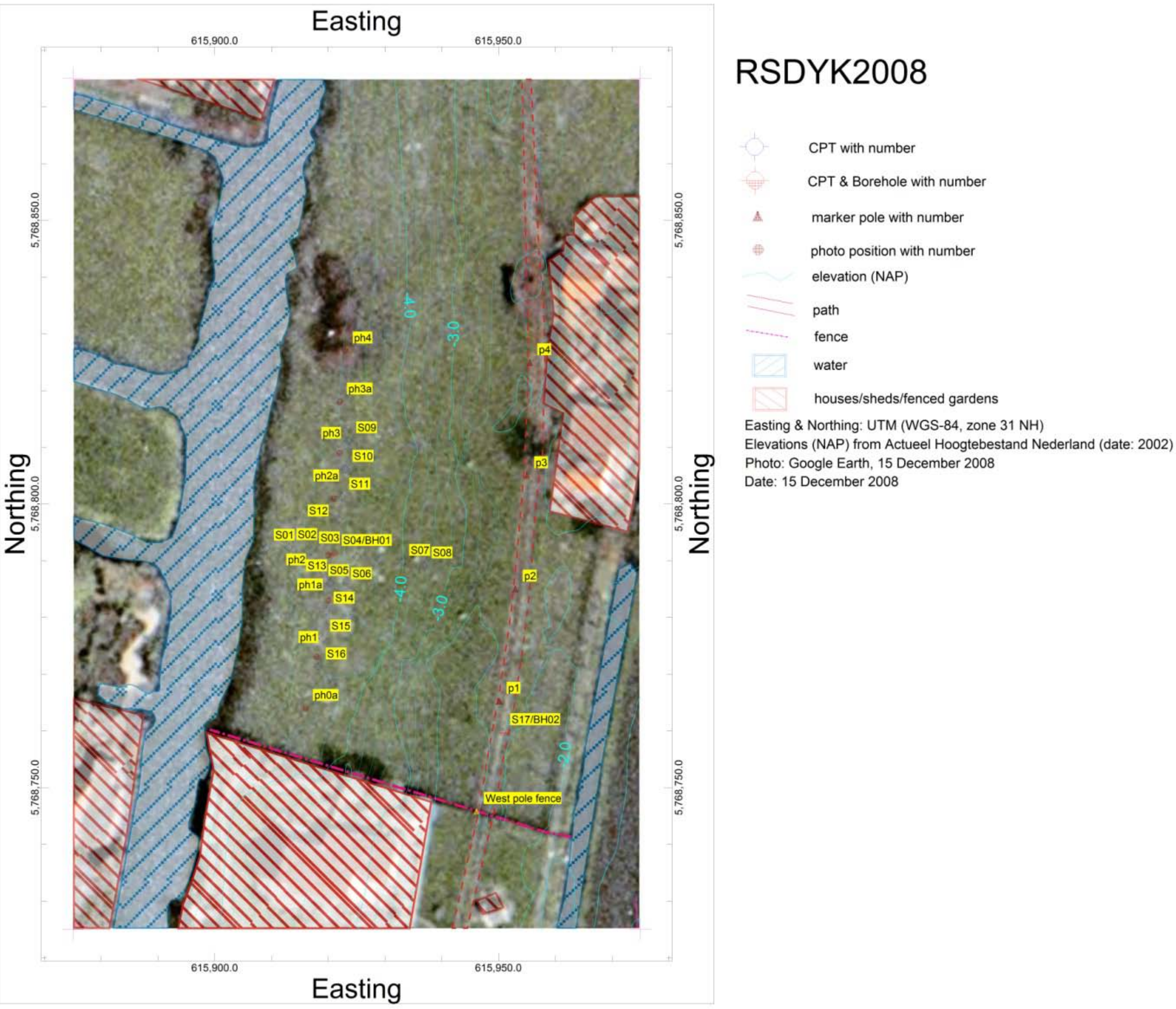

Figure 4-1. Tempeldijk-South test site area Boreholes and CPT

At the location of Tempeldijk-South two boreholes and 17 CPTs (Dutch Cone Penetration tests) with pore water pressure measurement have been made. The locations, and borehole, including photo logs, and CPT logs are included in appendix E. Direct besides a borehole also a CPT test has been made to facilitate interpretation of the CPT. The boreholes are made with a so-called “Delft Continuous Soil Sampler” (a type of triple-tube core sampler). Borehole logs have been made by visual description of the borehole cores.

4.2 Subsurface modeling

4.2.1 INTRODUCTION

The borehole and CPT logs obtained at Tempeldijk-South have been included in a three-dimensional geological model. Sections are included in appendix F. The interpretation has been done starting with the description of the boreholes coupled to the nearby CPT. In-between the CPTs the lithology identification has been done loosely following the standards commonly used in The Netherlands and international standards (Abu-Farsakh et al., 2008, Robertson, 1990) for CPT interpretation. Interpretation of soil lithology based on CPT data only and in particular details in peat and peat containing layers is notoriously difficult. Variations in type of plants remains or the competence of plant remains give changes in CPT values which are difficult to correlate to the visual description of the peat layers. For the purpose of this investigation especially the horizontal and vertical changes in lithology are likely very important. The differentiation of the lithology based on CPT values therefore has been done in as much detail as possible.

4.2.2 GENERALIZED SUBSURFACE CONDITIONS

The subsurface from the surface downwards can be generalized for the Tempeldijk-South location. The lithology names refer to the names used in the sections and 3D model in appendix G. The generalized composition of the dyke is:

- From the top a layer of clayey peat is present with a thickness of about 0.3 m in the East on top of the dyke reducing in thickness towards the west, the bottom of the dyke (PEATS). This layer is likely a man-made top layer.
- A sequence of peat and silty or clayey peat layers with some thin silt and clay layers is present between the man-made top layer and a depth of about – 5 m. In western directions these layers truncate against the man-made top layer (PEAT7, CLAY5, PEAT6, SILT3, and PEAT5).
- A fairly consistent clay clayey peat layer (CLAY4) is present at -5 m.
- Between about -5 and -9.5 to -10.5 a sequence of peat and silty or clayey peat layers with some thin silt and clay layers is present.
- At about -9.5 to -10.5 m an undulating sand layer sequence starts (SAND2).

4.3 Electrical resistivity

4.3.1 INTRODUCTION

The purpose of the electrical imaging survey is to determine the subsurface resistivity distribution of the sites. The resistivity of the subsurface materials is determined largely by the water content and secondary by the resistivity of the subsurface materials and the resistivity of the water. 2D and 3D resistivity surveys have been done. The 2D survey has mainly been used for determining the best array setup (appendices H and J).

4.3.2 2D RESISTIVITY

A 2-D electrical imaging survey is usually carried out using a large number of electrodes connected to a multi-core cable. The typical setup for a 2-D survey with a number of electrodes along a straight line attached to a multi-core cable is illustrated in Figure 4-2. A computer operated “Sting R1/IP” has been used as measuring device. It is a single channel automatic resistivity imaging device with a multi-electrode system. It has a built-in set of command files for different electrode arrays. Typically, 28 electrodes are laid out in two strings of 14 electrodes, with electrodes connected by a multi core cable to a switching box and resistance meter (Figure 4-3). The electrode spacing has been 1 m.

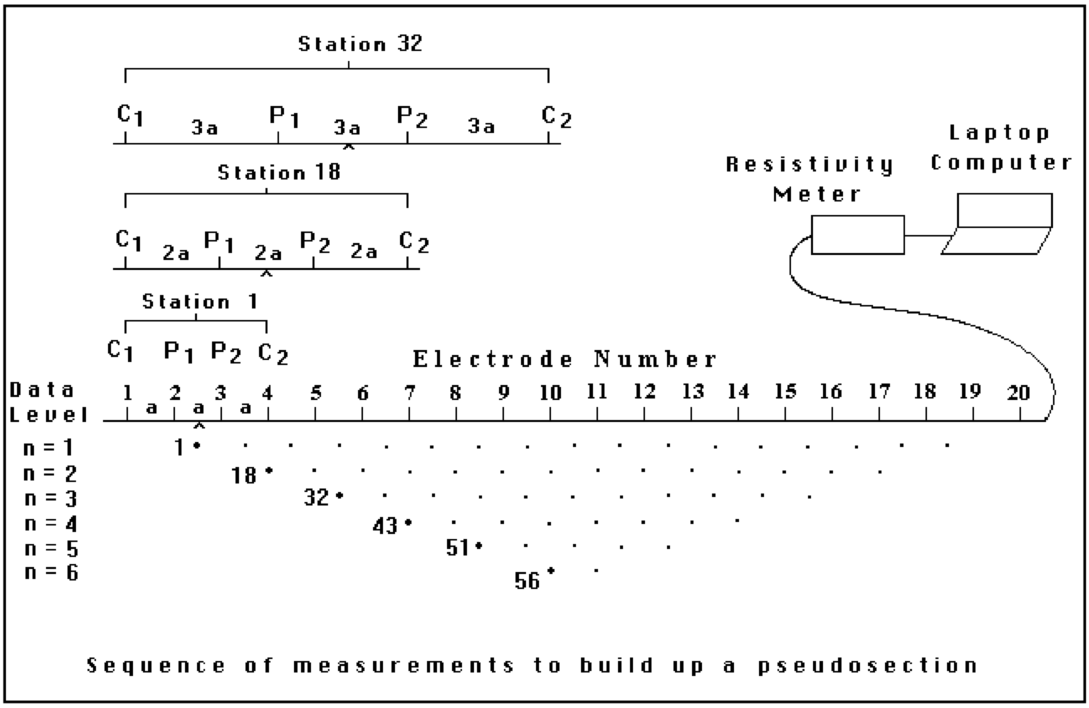

Figure 4-2: The electrode arrangement for a 2-D electrical imaging survey and the sequence of measurements used to build up a pseudo-section (Loke M.H., 2000).

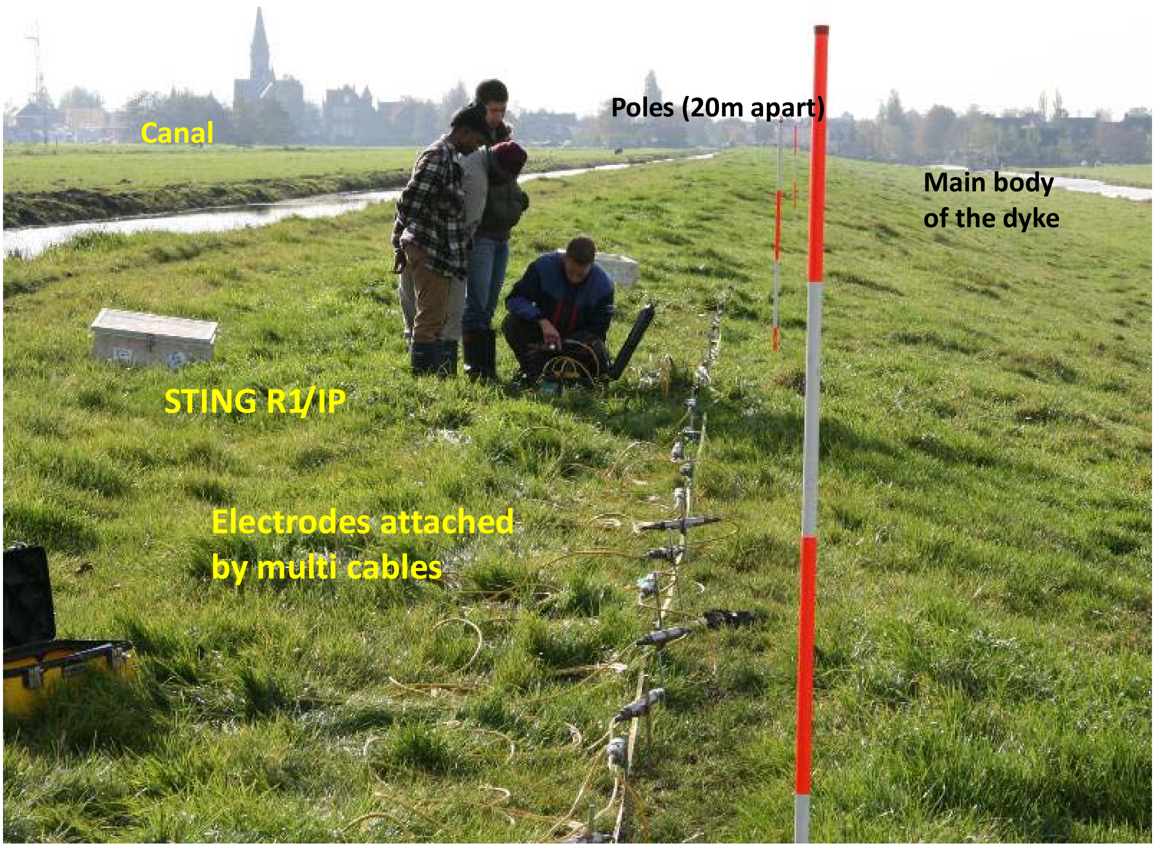

Figure 4-3: A 2-D electrical imaging survey on the Tempeldijk-North. The equipment consists of a Sting R1/IP and 28 electrodes having a 1 m spacing laid out in two strings of 14 electrodes.

4.3.3 ADVANTAGES AND DISADVANTAGES OF THE THREE ARRAYS

In 2-D imaging surveys, the electrode setups “Schlumberger”, “Wenner” and “dipole-dipole” are the electrode arrays that are the most commonly used. The choice of the “best” array for a field survey depends on the type of structure to be mapped, the sensitivity of the resistivity meter and the background noise level. The Wenner array is relatively sensitive to vertical changes (i.e. horizontal structures) in the subsurface resistivity below the centre of the array. However, it is less sensitive to horizontal changes (i.e. narrow vertical structures) in the subsurface resistivity. The dipole-dipole array is most sensitive to resistivity changes between the electrodes in each dipole pair and the sensitivity contour pattern is almost vertical. This array is therefore very sensitive to horizontal changes in resistivity, but relatively insensitive to vertical changes in the resistivity. Unlike the above arrays, the Schlumberger array is moderately sensitive to both horizontal and vertical structures. In areas where both types of geological structures are expected, this array might be a good compromise between the Wenner and the dipole-dipole array.

4.3.4 3D RESISTIVITY SURVEY

A full three-dimensional resistivity survey has been done on the location Tempeldijk-South. The results are included in appendix G.

4.3.5 CORRELATION BETWEEN 3D RESISTIVITY SURVEY AND SUBSURFACE MODEL AT TEMPELDIJK-SOUTH

The resistivity imaging of the subsurface at Tempeldijk-South can fairly accurately be related to the subsurface lithology model. The low resistivity vales correlate to peat layers and in particular to more silty or sandy peat layers. In the top part of the dyke (e.g. above -5 m) the low resistivity values correlate with a silt or silty peat layer (refer to appendix H, figures H-4 and H-5) in which the silt layer is indicated with SILT3.

5 IMAGING

5.1 Visual, Thermal InfraRed (TIR) and Near-InfraRed (NIR)

In appendix I and J are included the analysis of the remote sensing images (appendix I) and the correlation analyses between the remote sensing images and 2D resistivity surveys (appendix J).

5.2 Gamma Ray survey

In appendix K the results of the gamma ray survey are included.

5.3 Hyper Spectral Survey

In appendix L are included the analysis of the hyper spectral survey.

6 DISCUSSION, CONCLUSION AND RECOMMENDATION

6.1 Discussion

The soil moisture content is one of the most important parameter affecting surface stability in soil structures and hence in the typical peat dykes found in the western part of the Netherlands. In peat, the effective stresses and shear strength that are determining the stability are directly related to the water content. Since the distribution of water content and also the properties of the materials in dykes vary both vertically and horizontally, the stability of the peat dykes is also highly variable vertically and horizontally. This highly variable nature and the enormous length of so-called peat dykes make that assessment of the stability on a regular basis is a costly affair. Therefore, any means that would be able to assess the stability or even to indicate only changes in the stability that are cheaper than the presently used visual inspections are worthwhile to be investigated on their merits. Remote sensing is thought to be a possible assessment method, and therefore is in this research is investigated how far remote sensing techniques could determine variations in water and soil properties of the dykes.

6.1.1 VISUAL

The visual images show obviously mainly that surface and thus the surface vegetation cover of the dyke. The vegetation cover, however, may show also differences in vegetation cover, such as the presence of small yellow flowers in part of the foot of the dyke (Tempeldijk-South, appendix I, Figure 6). It is remarkable that this location more or less coincides with the location where possible excess water flows out of the dyke. It is not unlikely that locations that are wetter also have a vegetation cover that is different from those covering more dry areas.

6.1.2 ELEVATION DATA

Although not intended to be investigated in this pilot study, the data from the Algemeen Hoogtebestand Nederland may show deficiencies in a dyke. The data determined by Lidar surveys is accurate enough to determine surface patterns with high detail. The Tempeldijk-South location shows a pattern that may indicate a deficiency (subsidence) at a location where also the layers in the subsurface (determined from the three-dimensional resistivity survey and 3D subsurface model) show variations in elevation. Visually any deficiency in the surface of the dyke has not been noted.

6.1.3 THERMAL INFRARED (TIR)

The geotechnical properties of peat differ from those of clay in many aspects. Compared to clay, peat has a much higher porosity and ability to hold water under natural (unloaded) conditions. This was clearly indicated from their ability to absorb and emit electromagnetic energy. Apart from the emissivity property of the material composition, the emissivity of an object is highly depending on the moisture content. Water has very dark to medium gray tones in day TIR images and moderately light tones in night TIR images, compared with the soil. This simply means that water is cooler in the day and warmer in the night than most other materials present. This response is due in part to a rather high thermal inertia, relative to typical land surfaces, as controlled largely by water's high specific heat. After prolonged period of rainfall, in this research thus mainly in the autumn and winter, when the topsoil water content is high, the heat capacity of the topsoil is also high and as a result, more energy is needed to increase its temperature. In consequence, the surface temperature response to solar radiation and air temperature is slower and weaker. However, after a long period without rain the water content of the soil is less, and surface temperatures responds quicker to solar radiation and air temperatures. This feature is shown by the multi-temporal TIR images of Tempeldijk-South. During the summer following the reduction of the moisture content due to evaporation and evapo-transpiration from the topsoil, the peat layer becomes dry and has higher temperatures where as during the winter it becomes wet and has low temperatures.

Since the dykes are covered with grass, the radiation temperature values are the resultant of the emitted temperatures from the topsoil of the dyke material and the grass. It is difficult to establish how much of this resulted from the grass compared to that from the topsoil. The variation in the radiation temperature of the grass is mainly related to the accumulation of the rainfall water. Fallen debris from the grass (dead leafs), the water content in the soil, the apparent roughness, and the position with respect to the sun also influence the radiation. The radiation temperature variation of the dyke materials is mainly related to the seasonal variability of water content in the soil water content and therefore can probably be related to the geotechnical properties of the dyke materials.

6.1.4 RESISTIVITY SURVEYS

The results of the 2-D electrical imaging surveys identify the stratigraphic profile of the two sites on the Tempeldijk. The interpolated pseudo-sections reveal the geological formation of the dyke. The boundary between the clay layer and the peat layer was clearly determined. Also lateral variations were established that may indicate heterogeneity of these layers, however, also variation in water content may be present. In the lower parts also more salt containing water from the sub-surface seepage from deeper layers may be present which is shown by low resistivity values.

6.1.5 CORRELATION TIR IMAGES AND 2D RESISTIVITY SURVEYS

A qualitative analysis was made between the TIR images and the 2-D electrical imaging results to describe their similarities and/or differences. Similarities were noted between the high resistivity and the low radiation temperature as well as between low resistivity and high radiation values (appendix J).

In both techniques it is difficult to differentiate the compositional variation of the subsurface from the variation due to moisture content or other factors. The main reason can be the variation in the geotechnical properties of the unconsolidated soils that can vary within a small distance. For instance, the distribution of water content and total unit weight of a peat layer varies in all directions (vertically and horizontally). The variations perpendicular to the survey line are not indicated by the 2-D electrical imaging survey. This is because the 2-D electrical imaging survey assumes there is no change in the third dimension. On the other hand, the TIR images have information of the top layer (surface) 0.5 – 1 m. however the distance between these images range from 1 m on the top up to 20 m and more at the bottom part of the dyke. The grass that covers the dyke materials is also an influencing factor. The presence of the grass minimizes the possible interaction between the topsoil and the solar radiation. This implies that exposed dyke materials react to the solar radiation and atmospheric temperature quicker than covered once.

6.1.6 NEAR INFRARED (NIR)

Differences in the reflectance of the grass were observed in the multispectral images of the NIR. Variations in the reflectance are mainly related to the vegetation properties such as the leaf area, biomass, chlorophyll concentration in leaves, plant productivity, vegetation cover, accumulated rainfall etc. The apparent roughness of the grass, position of sun angle and wind direction was considered as additional influencing factors. These properties change with respect to seasonal variations. Plots of TIR verses NIR images of the same season were also evaluated to establish possible relationship between the thermal radiation and the reflectance values. However, there is not any indication in the trend of the relationship. This is shows that both images are governed by different factors. Moreover their wavelength propagation of the TIR and NIR belongs to the different portion of the electromagnetic spectrum. The relationship between the TIR and NIR of the dykes did not reflect the inverse relationship of the Kirchhoff's law.

6.1.7 CORRELATION REMOTE SENSING, RESISTIVITY AND SUBSURFACE MODEL

The 3D resistivity survey shows low values in the top part of the dyke (above -5 m) where possibly a silt or silty peat layer is present based on the 3D subsurface model. This location coincides with a location where the surface of the dyke is softer or weaker. A softer surface in a dyke occurs when the surface contains a higher water content and in particular if an upward water flow exist. The low values of resistivity may therefore indicate that a water flow exist from the east side of the dyke which comes to surface at the west side and causes the "kwel". The remote sensing with visual light shows at this location a high quantity of grasses or plants with small yellow flowers. These flowers were not or only seldom seen at other locations.

6.2 Conclusions Pilot study

Main conclusions of this pilot study are:

- The comparison of the reference site (Tempeldijk-North) with Tempeldijk-South (a known "problem" location) shows that in all surface and subsurface investigations the Tempeldijk-South surface and subsurface structure are more irregular which are due to or indicate "problems' such as "kwel" and subsidence.
- The thermal infrared images of Tempeldijk-South showed a layered structure which is reflecting the subsurface structure of the dyke. The layered structure was detectible likely because excess water was present in some of the layers.
- Visual images showed differences in vegetation cover at locations where excess water is likely present.
- The gamma ray survey shows a pattern that is likely related to the real subsurface structure, but further investigations are required to determine the exact nature of this relation.
- The 3D subsurface model and 3D resistivity model correlate.
- The data from the Algemeen Hoogtebestand Nederland may show patterns indicating deficiencies in a dyke. The data determined by Lidar surveys is accurate enough to determine surface patterns with high detail.

A quantitative analysis was used to evaluate the relationship between the TIR and the NIR images. Scatter plots were made between the radiation temperature and reflectance DN-values. Most of the plots illustrate a very weak relationship. Some of the influencing factors are:

- Multi-spectral near infrared only provides surface information that is the reflectance from the grass while the thermal radiation includes information about the topsoil of the dyke.
- Reflectance is highly depending on the vegetation properties such as the leaf area, biomass, chlorophyll concentration in leaves, plant productivity, vegetation cover, accumulated rainfall etc.
- Position of the sun angle, apparent roughness and wind direction are also some of the external factors that affect the true reflectance.
- Color: darker objects absorb and emit more than the lighter colored objects
- Surface roughness: the greater the roughness (compared to λ) will have the greater the surface area and the greater the emission.
- The seasonal variation and the physical change in the grass between the field campaign periods was the main factor affecting the relationship of the multi-temporal images.
- Supplementary information might derive from the NIR but it might be difficult to detect stressed grasses and determine the distribution of moisture content of the dyke using only the ADC multi-spectral camera.

6.3 Recommendations

- Thermal emissivity is highly dependent on the moisture content of a soil and thus the emissivity of this moisture content can vary with diurnal period. Therefore, it is important to acquire thermal images in different hours of the day in order to see the variation in the emissivity of the dyke materials and to indicate the distribution of moisture content of the topsoil.

- Two objects might have the same T_{kin} (kinetic temperature) but have different T_{rad} (radiation temperature) because of differences in their emissivity and their emissivity can be influenced by external factors such as moisture content, color, and surface roughness. In situ measurement of the surface temperature of the dyke materials using digital thermometers is very important to understand the degree of the influence from these factors and to calibrate the results of the thermal images.
- Local meteorological variables have to be measured simultaneously with the TIR imaging in order to characterize the conditions of the sensor-ground surface continuum. These included air temperature and the global radiation reaching the surface.
- The remotely sensed imaging should have to be acquired perpendicular to the study interest, by increasing the platform above the ground. This will help to minimize the scattering effect in the reflection for the near infrared imaging.
- Vegetation stress can possibly be detected better using hyper spectral remote sensing. Using spectroscopy it will be easier to differentiate the stressed grass from the healthy grass based on their variation in the reflectance spectral signature. Therefore, it might be better to use hyper spectral spectroscopy in the future study.