NAM

Background document NAM database of subsurface information
Version date of database - 29 March 2018

Deltares,

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Date   March 2018

Editors   Jan van Elk & Dirk Doornhof

General Introduction

Deltares has prepared a detailed geological model of the shallow sub-surface (Ref. 1 to 3) used in studies into site response for the hazard assessment (Ref. 4) and studies into liquefaction potential (Ref. 5). These models are based on data collected from various data sources extended with additional data collected (Ref. 6).

All this data has been collected in a Rockworks® database. This note describes the version of this database as at end-March 2018 and introduces the data stored consisting of borehole data, CPT, Seismic SCPT and multi-tool interpretation of logged boreholes.

References

1. Geological schematisation of the shallow subsurface of Groningen (For site response to earthquakes for the Groningen gas field) – Part I, Deltares, Pauline Kruiver, Ger de Lange, Ane Wiersma, Piet Meijers, Mandy Korff, Jan Peeters, Jan Stafleu, Ronald Harting, Roula Dambrink, Freek Busschers, Jan Gunnink
2. Geological schematisation of the shallow subsurface of Groningen (For site response to earthquakes for the Groningen gas field) – Part II, Deltares, Pauline Kruiver, Ger de Lange, Ane Wiersma, Piet Meijers, Mandy Korff, Jan Peeters, Jan Stafleu, Ronald Harting, Roula Dambrink, Freek Busschers, Jan Gunnink
3. Geological schematisation of the shallow subsurface of Groningen (For site response to earthquakes for the Groningen gas field) – Part III, Deltares, Pauline Kruiver, Ger de Lange, Ane Wiersma, Piet Meijers, Mandy Korff, Jan Peeters, Jan Stafleu, Ronald Harting, Roula Dambrink, Freek Busschers, Jan Gunnink
4. Modifications of the Geological model for Site response at the Groningen field, Deltares, Pauline Kruiver, Ger de Lange, Ane Wiersma, Piet Meijers, Mandy Korff, Jan Peeters, Jan Stafleu, Ronald Harting, Roula Dambrink, Freek Busschers, Jan Gunnink
5. Liquefaction sensitivity of the shallow subsurface of Groningen, Deltares and TNO-GSN: Mandy Korff, Ger de Lange, Piet Meijers, Ane Wiersma, Fred Kloosterman, November 2016.
6. Geophysical Measurements of shear wave velocity at KNMI accelerograph stations in the Groningen field area, Deltares, Marco de Kleine, Rik Noorlandt, Ger de Lange, Marios Karaoulis and Pauline Kruiver, July 2016.

Title	**Background document NAM database of subsurface information** **Version date of database - 29 March 2018**	**Date**	August 2018
		Initiator	NAM
Autor(s)	**Pauline Kruiver, Fred Kloosterman, Ger de Lange, Pieter Doornenbal**	**Editors**	Jan van Elk and Dirk Doornhof
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Place in the Study and Data Acquisition Plan	<u>Study Theme:</u> Shallow Geology and Soil Description <u>Comment:</u> Deltares has prepared a detailed geological model of the shallow sub-surface used in studies into site response for the hazard assessment and studies into liquefaction potential. These models are based on data collected from various data sources extended with additional data collected. All this data has been collected in a Rockworks® database. This note describes the version of this database as at end-March 2018 and introduces the data stored consisting of borehole data, CPT, Seismic SCPT and multi-tool interpretation of logged boreholes.		
Directliy linked research	(1) Ground Motion Prediction (2) Liquefaction (3) Active Clays		
Used data			
Associated organisation	TNO-GSN		
Assurance			

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Deltares

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1209862-004

Deltares

Title
Background document NAM database of subsurface information

Client	Project	Reference	Pages
Nederlandse Aardolie Maatschappij B.V.	1209862-004	1209862-004-GEO-0001	21

Keywords
Database, borehole descriptions, borehole logging, cone penetration tests, seismic cone penetration tests, Rockworks®

Summary
The NAM database, containing subsurface information from borehole descriptions, borehole logging, cone penetration tests and seismic cone penetration tests from various sources, has been updated and synchronised. The version date of the Rockworks® database is 29 March 2018. Different components of the database, however, have different update dates, which are specified in the document. This document describes the background of the various components in the database.

References
Contract UI46802 "Studies on the soil in Groningen"

Version	Date	Author	Initials	Review	Initials	Approval	Initials
4	August 2018	Pauline Kruiver	P.K.	Mandy Korff	MK	Renée Talens	RJa
		Fred Kloosterman					
		Ger de Lange					
		Pieter Doornenbal					

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Contents

Appendices

1 Introduction

The geological model for site response (Kruiver et al., 2015, 2018) and for liquefaction (Korff et al., 2016) are developed from various data sources about the subsurface. These data include geological models of various depth ranges and point source information from boreholes and cone penetration tests (CPT's). The boundary of the geological models and the background data is defined by the 5 km buffer around the outline of the Groningen gas field (Figure 1.1).

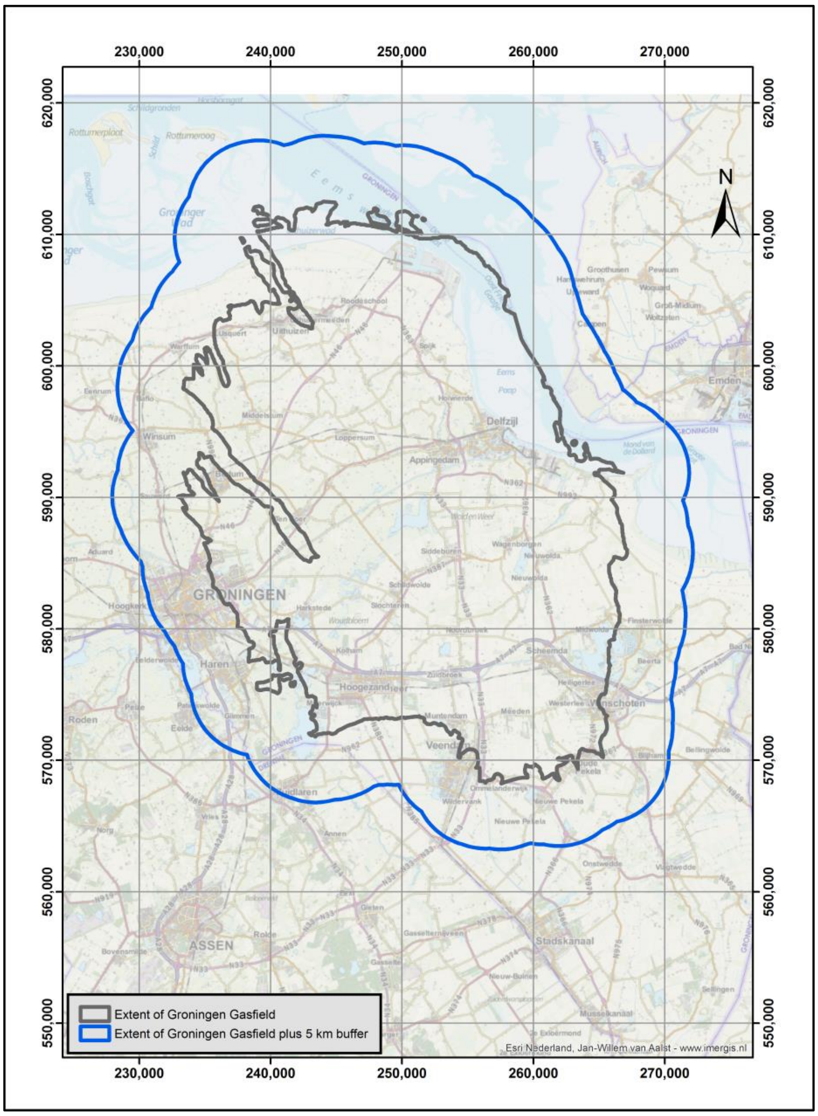

Figure 1.1 Area of interest defined by a 5 km buffer around the outline of the Groningen gas field.

At the start of the geological model development in September 2014, the borehole descriptions and CPT's from Dinoloket were included in the database for NAM. During the development, two datasets with CPT's from Wiertsema & Partners and Fugro were gradually added to the database, filling gaps in the DINO coverage. The Rockworks® database was delivered to the NAM on 19 December 2014. On 31 March 2015, a first set of Seismic CPT's

(SCPT), provided by Arup, were added to the Rockworks® database. This set largely contained the SCPT's that were performed in the framework of the earthquake hazard project up to that date.

Various projects and independent societal developments generated additional data. These data include the borehole logs at the vertical seismic array stations (Doornenbal et al, 2015a, b), SCPT's at surface accelerograph stations (de Kleine et al., 2016, Noorlandt et al., 2018) and at the Eemskanaal levee (Nikkels, 2016) and CPT's at various urban centres in the area performed for the organisation "Centrum Veilig Wonen" (CVW, 2016). The CPT's were received by Deltares from NAM in the period from July 2017 until March 2018. In the autumn of 2017, NAM commissioned the synchronisation of the various databases. The current database, dated officially 29 March 2018, is the result of the synchronisation.

The first batch of borehole and CPT data of the gas field was delivered to NAM as Rockworks® version 16 projects. In addition, digital presentations of the data and graphs of borehole and CPT logs were provided. The presently updated data is now stored in Rockworks® version 17 SQLite databases and only for the newly added boreholes and CPT's digital presentations of borehole and CPT logs have been generated.

This document describes the background of the database version 29 March 2018. Chapter 2 gives an overview of the components of the database. Chapters 3 to 6 include the background information about the components and definitions of the formats. Chapter 3 describes the borehole descriptions, chapter 4 the CPT's and chapter 5 the SCPT's. The borehole logging is described in chapter 6. Relevant references are included in appendix A.

2 Overview of content of database version April 2018

The content of the database is summarised in Table 2.1. The various components are described in more detail in the following chapters.

Table 2.1 Components of the Rockworks® database.

Source	Reference	Type of data	Amount of data	Date
Dinoloket	www.Dinoloket.nl	Borehole descriptions	19,902 boreholes, of which 10,594 with full lithology descriptions according to standards of Geological Survey of the Netherlands (RGD)	5 April 2018, updated extraction from Dinoloket
Dinoloket	www.Dinoloket.nl	CPT	1,705, including 114 CPT's with incomplete records, q_c only	2012 till 2018
Fugro, Wiertsema & Partners, Arup and others, including CVW	Various	CPT	5,229	From autumn 2014 till March 2018
Arup, Wiertsema & Partners, Fugro	Villani & Neto, 2014	SCPT	62	In the course of 2014
Deltares, fieldwork at accelerograph stations	De Kleine et al. 2016	SCPT & CPT	27	October 2015
Eemskanaaldijk (Fugro)	Nikkels, 2016	SCPT & CPT	20	June 2016
Various (see Table 5.1)	Various	SCPT	67	Until March 2018
Deltares	Doornenbal et al., 2015a,b	Gamma borehole logging	53	October 2015
Deltares	Doornenbal et al,, 2015a	Sonic borehole logging	7	September 2015

3 Borehole descriptions

3.1 General

DINO is the central database containing data of the Dutch subsurface. This database is maintained by TNO Geological Survey of the Netherlands. The database contains both the raw subsurface data and derived regional geological models. Much of the data has been submitted by companies, government authorities and the general public. The oldest records date back to the 19th century and regularly new data is added.

Updates of the borehole descriptions from the DINO database were downloaded in September 2014 for the development of the geological models. For the synchronisation with the NAM database, a final complete extraction of Dino database was provided by TNO on 5 April 2018.

The database contains 19,902 boreholes. The locations of all boreholes are shown in Figure 3.1. Figure 3.2 shows the locations of the Dino boreholes newly added to the database.

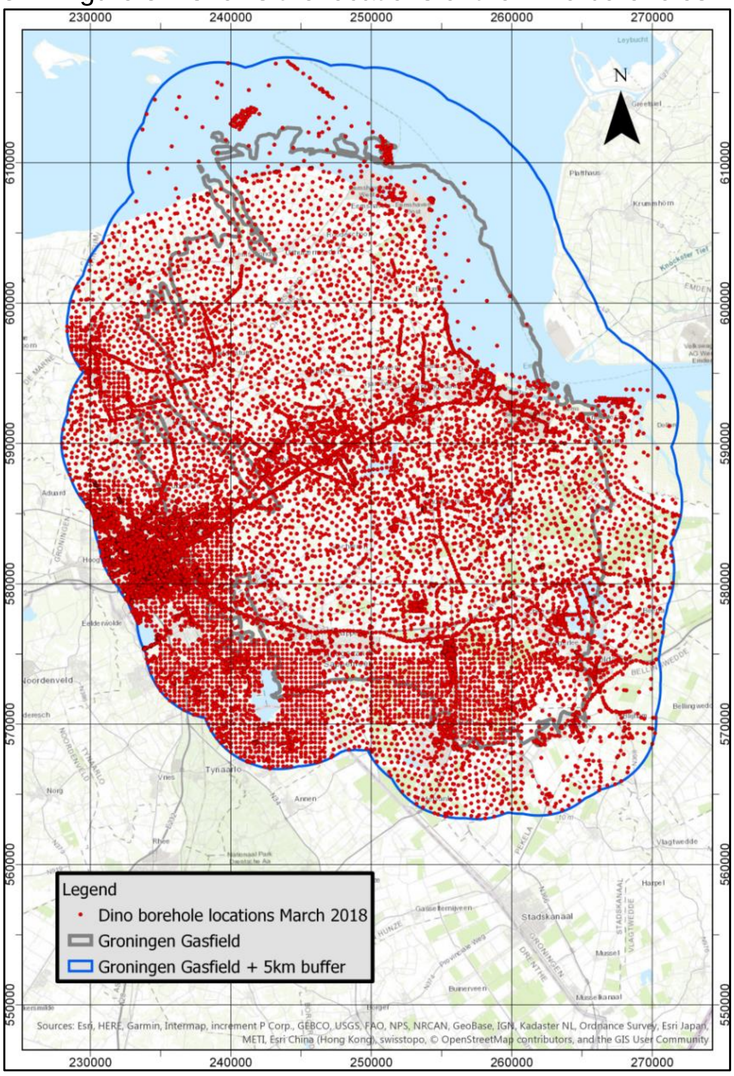

Figure 3.1 Map of DINO borehole locations (n=19,902 of which n=10,594 with detailed RGD descriptions).

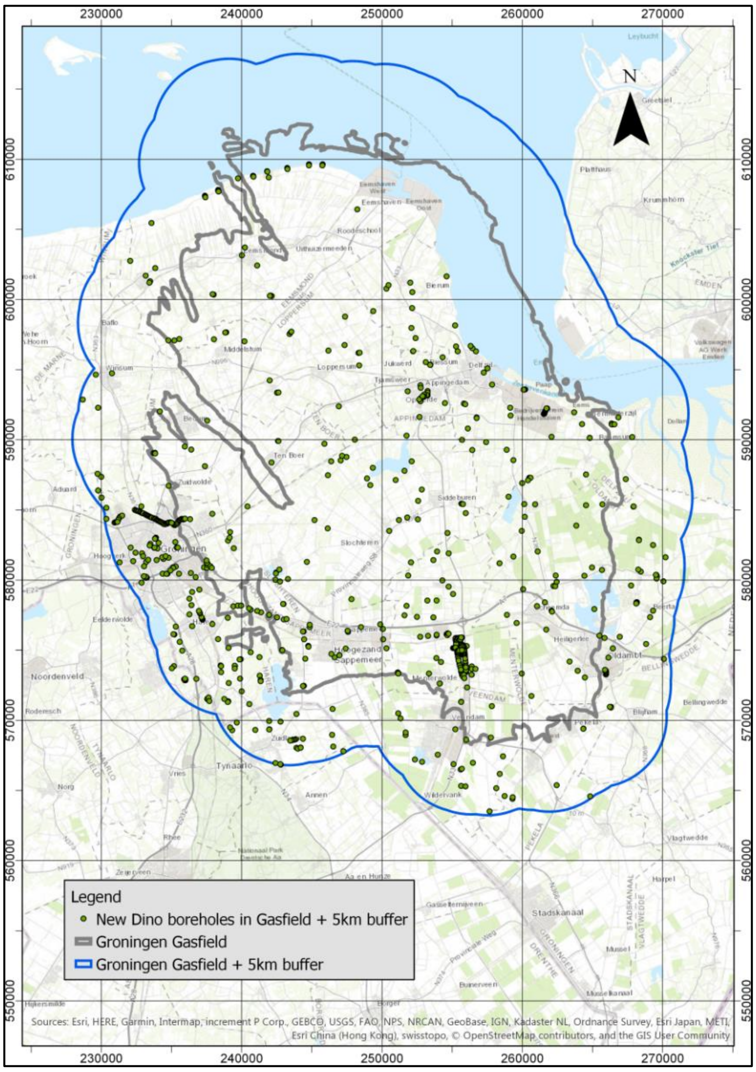

Figure 3.2 Map of new DINO borehole locations drilled after July 2015 (n=957).

For more than half of the boreholes (10,594) there are detailed RGD (former “Rijks Geologische Dienst”, now Geological Survey of the Netherlands) descriptions of the penetrated lithologies available.

The depth of the boreholes ranges from 0.5 to 304 m below the surface. The statistical distribution of the total depths of the Dino borehole population is shown in the histogram of Figure 3.3. Note the highly skewed distribution with the majority of boreholes not surpassing depths of about 10 m.

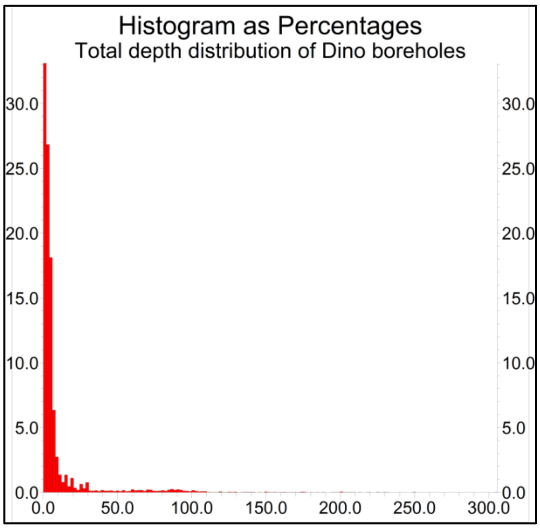

Figure 3.3 Histogram of the total depth distribution of the Dino boreholes.

3.2 Format

The borehole data with all attributes in terms of lithology and stratigraphy are stored in a Rockworks® version 17 SQLite database. The lithology is stored as colour, grainsize class, the original RGD detailed lithology description and as a code. However, the RGD layer descriptions are not available for all boreholes stored in the database. The technical format of the tables holding the borehole descriptions in the database is specified in Table 3.1. Table 3.2 presents an overview of the secondary lithological properties also stored in the Rockworks® database as a result of the full Dino extraction.

Table 3.1 Format of tables in the Rockworks® database storing the primary borehole descriptions.

RockWorks Table	Fields	Data Description
Location	BhId	Unique numerical id code of a borehole, database key
	Name	Official DINO Borehole name
	Easting	X coordinate in Rijksdriehoekstelsel_New
	Northing	Y coordinate in Rijksdriehoekstelsel_New
	Elevation	Elevation in m. NAP
	TotalDepth	Total depth in m.
	dd_lon	Longitude in WGS84
	dd_lat	Latitude in wgs84
	lcs_x	X coordinate in Rijksdriehoekstelsel_New
	lcs_y	Y coordinate in Rijksdriehoekstelsel_New
LithType	LithTypeId	Unique identification numerical code, database key
	Name	Combination of extended lithology, colour and grainsize class
	Patterns....	Drawing Patterns in the borehole lithology columns
	Background	Drawing colours in LongInt numerical format
	Foreground	Drawing colours in LongInt numerical format
	FillPercentage	Width of the lithology columns in graphics
StratType	StratTypeId	Unique identification numerical code, database key
	Name	DINO name of geological formations and layers (2003 Stratigraphical Terminology)
	Patterns....	Drawing Patterns in the borehole stratigraphy columns
	Background	Drawing colours in LongInt numerical format
	Foreground	Drawing colours in LongInt numerical format
	FillPercentage	Width of the stratigraphy columns in graphics
Lithology	BhId	Key referring to the Location table
	Depth1	Top of the lithological layer in m. below the surface
	Depth2	Bottom of the lithological layer in m. below the surface
	LithTypeId	Key referring to the LithType table
	Comment	Original RGD lithology description
Stratigraphy	BhId	Key referring to the Location table
	Depth1	Top of the stratigraphical in m. below the surface
	Depth2	Bottom of the stratigraphical layer in m. below the surface
	StratTypeId	Key referring to the StratType table
	Comment	Original RGD Litho-stratigraphy

Table 3.2 Overview of the secondary lithological properties, stored in the Rockworks® tables Interval and Text.

Database_code	Description
Calcite_contents	Calciumcarbonate contents class
Clay_contents	Clay contents class
Color	Color code
Consistency	Lithological consistency
Glauconite_fraction	Glauconite fraction
Gravel_contents	Gravel contents class
Mica_fraction	Mica minerals fraction
Mud_contents	Mud contents class
Organics_contents	Organics contentss class
Plant_fraction	Plant materials fraction
Sand_contents	Sand contents class
Sand_median_class	Sand median class types
Shell_contents	Shell contents class
Silt_contents	Silt contents class
Stratigraphy_1975	Obsolete stratigraphy codes 1975
Stratigraphy_2003	Stratigraphy codes 2003
Clay_fragments	Presence of clay fragments
Lutum_perc	Lutum content
Organics_perc	Organics content
Plants_present	Presence of plant materials
Sand_median	Grain size median
Shells_present	Presence of shells

4 CPT

4.1 General

During a standard Cone Penetration Test (CPT) the cone tip resistance q_c and the friction sleeve resistance f_s is measured. Recently, pore pressure u_1 or u_2, measured respectively on the cone or behind the cone is registered as well. The sleeve friction is often divided by the cone resistance and reported as the friction ratio R_f in percentages. CPT readings can be converted into various parameters such as undrained shear strength or soil type using empirical relations.

The CPT's from in the database are collected from a number of sources, summarised in Table 4.1. The locations of the CPT soundings are shown in Figure 4.1.

Table 4.1 CPT data sets in Rockworks® database.

Source	q_c and f_s	q_c, f_c and u_1/u_2
DINO loket	1,591 (+ 114 with q_c only)	0
Fugro, Wiertsema & Partners and others	3,823	2,024

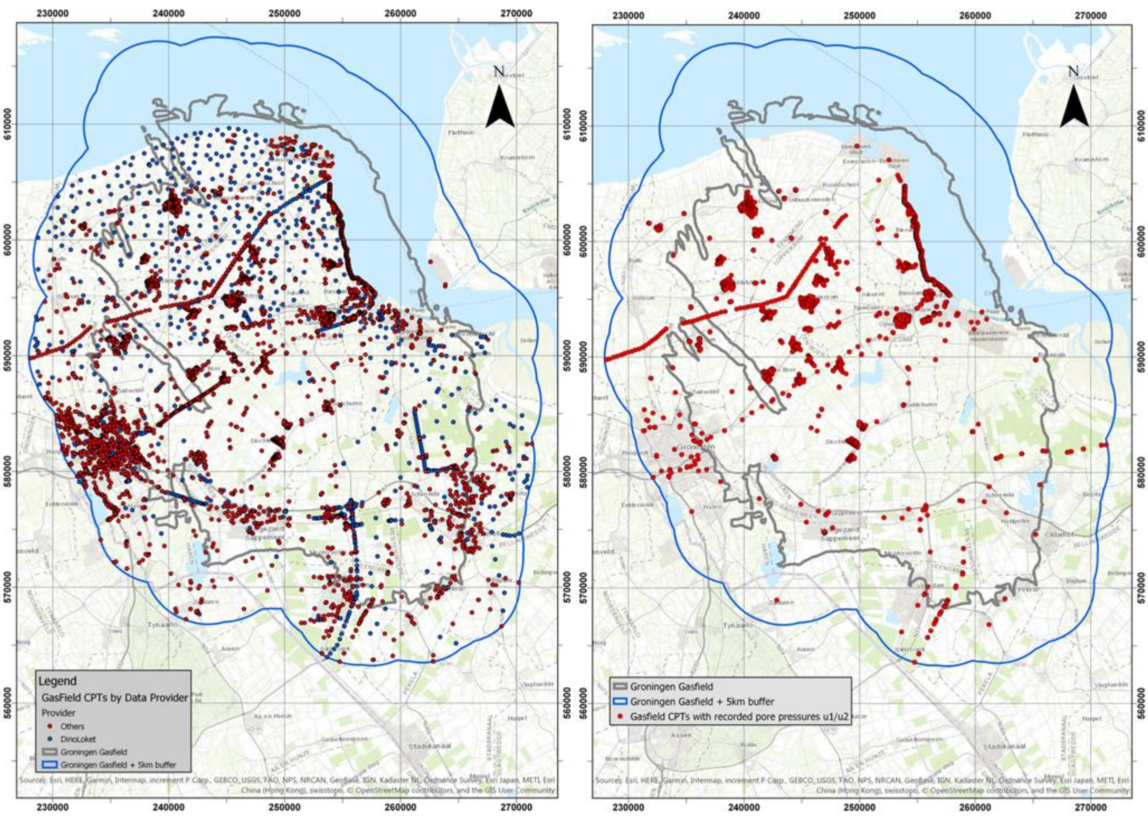

Figure 4.1 Map of CPT locations in the Rockworks® database (left), CPT's with pore pressures u_1/u_2 (right).

The statistical distribution of the total depths of the CPT's is shown in the histogram of Figure 4.2. The majority reaches to a depth of 30 m.

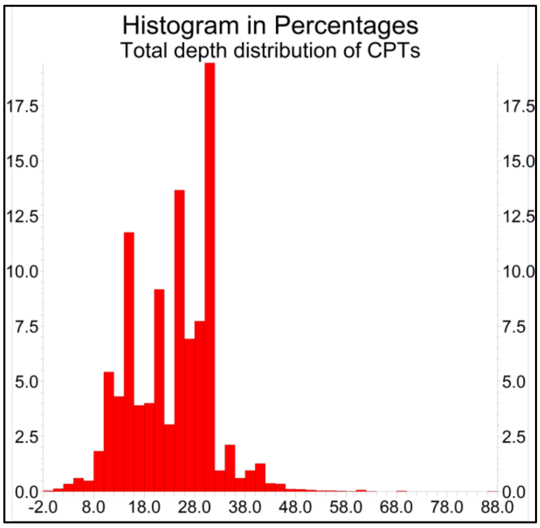

Figure 4.2 Histogram of the total depth distribution of the CPT's.

4.2 Format

The recorded raw CPT parameters and units as gathered from the data providers are listed in Table 4.2. The CPT parameters are generally recorded along 2 cm depth intervals. The interpreted lithology is derived by applying the Douglas & Olson (1981) soil classification of CPT data (cone resistance q_c and friction factor R_f). This classification was adjusted for the Groningen soil type distribution. The technical format of the database tables holding the raw CPT data in the Rockworks® database is specified in Table 4.3.

Table 4.2 Stored raw CPT parameters.

Name of CPT parameter	**Units**
Cone type and surface quotient	cm2
Cone Resistance	MPa
Local Friction	MPa
Friction Factor	%
Pore Water Pressure u1	MPa
Pore Water Pressure u2	MPa

Table 4.3 Format of tables in the Rockworks® database storing the CPT data.

RockWorks Table	Fields	Data Description
Location	BhId	Unique numerical id code of a borehole, database key
	Name	Official DINO Borehole name
	Easting	X coordinate in Rijksdriehoekstelsel_New
	Northing	Y coordinate in Rijksdriehoekstelsel_New
	Elevation	Elevation in m. NAP
	TotalDepth	Total depth in m.
	dd_lon	Longitude in WGS84
	dd_lat	Latitude in wgs84
	lcs_x	X coordinate in Rijksdriehoekstelsel_New
	lcs_y	Y coordinate in Rijksdriehoekstelsel_New
LithType	LithTypeId	Unique identification numerical code, database key
	Name	Combination of extended lithology, colour and grainsize class
	Patterns….	Drawing Patterns in RockWorks graphics
	Background	Drawing colours in LongInt numerical format
	Foreground	Drawing colours in LongInt numerical format
	FillPercentage	Width of the lithology columns in graphics
Lithology	BhId	Key referring to the Location table
	Depth1	Top of the lithological layer in m. below the surface
	Depth2	Top of the lithological layer in m. below the surface
	LithTypeId	Key referring to the LithType table
	Comment	Derived lithology according to Robertson methods
PointType	PointTypeId	Unique identification numerical code, database key
	Name	Name of the recorded CPT parameter
	MinValue	Minimum values estimated from the data set
	MaxValue	Maximum values estimated from the data set
	Units	Unit of recorded parameter
Point	PointId	Unique identification numerical code, database key
	BhId	Key referring to the Location table
	PointTypeId	Key referring to the PointType table
	Depth	Depth of the measured value in m. below the surface
	Value	Recorded value of the parameter

4.3 Quality of CPT data stored in Rockworks®

Classes of CPT's were not stored in the DINOloket database and not consistently present in the GEF files that were added to the Rockworks® database. Therefore, no information about the CPT class was included in the Rockworks® database.

After the synchronisation of CPT data with NAM database, there were duplicates in RD location coordinates (Rijksdriehoekstelsel coordinate system; easting and northing fields in the database). There were different CPT names on identical locations for a total of 247 CPT's. Many duplicates occur in the CPT data derived from the original Dinoloket database with data converted to the BRO database and subsequently downloaded from there. This was solved by checking the file names with a conversion table provided by Dinoloket. The elimination of duplicates was carried out by filtering on the basis of the coordinates. Special attention was paid to cases where multiple CPT's were recorded and stored in a project cluster with just one X,Y coordinate, in the data obtained from Fugro.

5 Seismic CPT

5.1 General

Seismic Cone Penetration Tests (SCPT's) are performed using a cone penetration tool equipped with a 2D or 3D geophone or accelerometer set. Fugro uses seismic cones equipped with two sets of triaxial orthogonal geophones that are mounted 0.5 m apart. Wiertsema and partners use one set of three orthogonal accelerometers. The SCPT penetration is interrupted at certain intervals. At these depths, a shear wave source at the surface, typically a wooden beam is hit with a sledgehammer, triggering the timed recording of the shear wave in the cone. Picking of the first shear wave arrival, combined with depth information and processing of the data, results in a shear wave velocity (V_S) profile versus depth. Standard procedure is to use depth intervals of 0.5 or 1 meter. The disadvantage of using a standard sampling interval is that stratigraphic boundaries generally do not coincide with the sampling locations. This results in bias of the V_S, especially in thin layers. In order to obtain V_S for a specific layer, the sampling depths were based on stratigraphy during the V_S fieldwork campaign of August 2015 (de Kleine et al., 2016, Noorlandt et al., 2018).

The Rockworks® database contains three datasets of SCPT, summarised in Table 5.1. The locations of the SCPT's are shown in Figure 5.1.

Table 5.1 SCPT data sets in Rockworks® database.

Data source / Project	Reference	Number of SCPTs	Depth range	Sampling Interval	Quality of Vs data
Archive until 2014	Villani & Neto, 2014	62	14.5-30.5	Standard 1.0 or 2.0 m	Variable
Accelerograph stations	De Kleine et al. 2016	27	18 – 30.5 m	Coinciding with stratigraphic boundaries	Very high
Eemskanaal levee	Nikkels, 2016	20	26 – 30 m	0.5 or 1.0 m	High (reprocessed)
Centrum Veilig Wonen (CVW)	Various reports	56	16 - 30 m	0.5 m	
Forum	Fugro Report 5012-0254-040	2	25	0.5 m	
Wadzanden Eemshaven-Delfzijl	Fugro Report 1016-0459-000	9	25 m	0.5 m	

The statistical distribution of the total depths of the SCPT's is shown in the histogram of Figure 5.2. The majority reaches to a depth of 30 m.

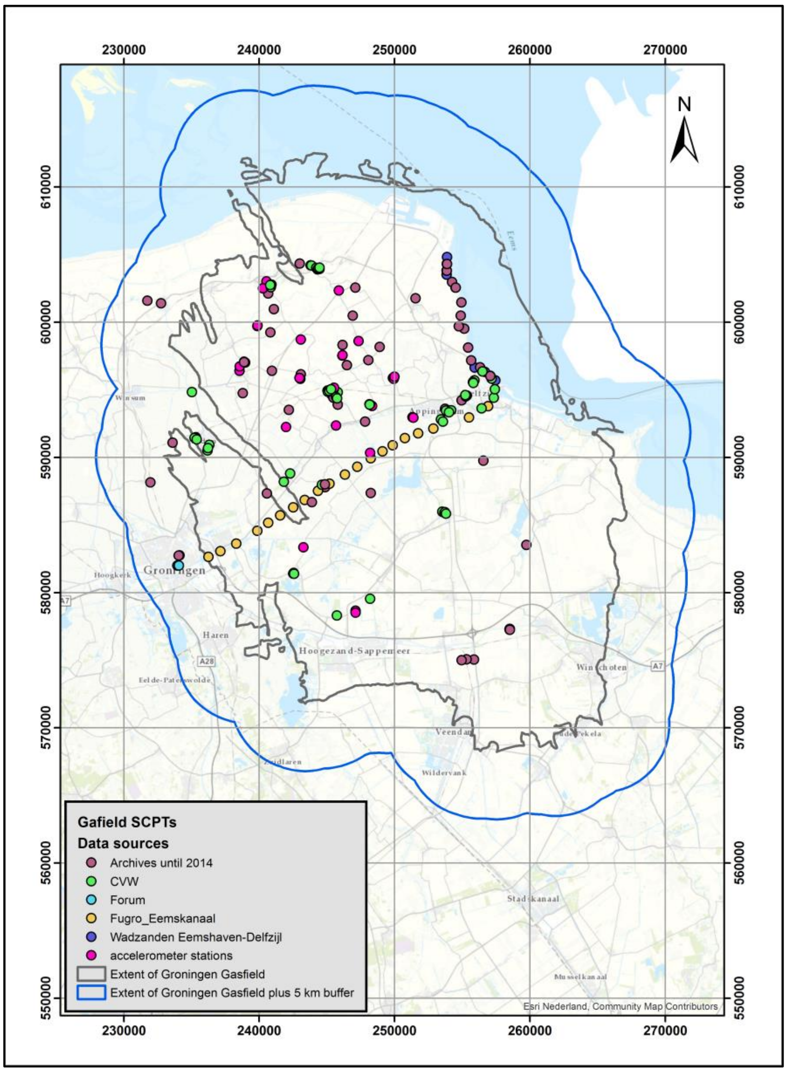

Figure 5.1 Map of SCPT locations (n=176) in the Rockworks® database.

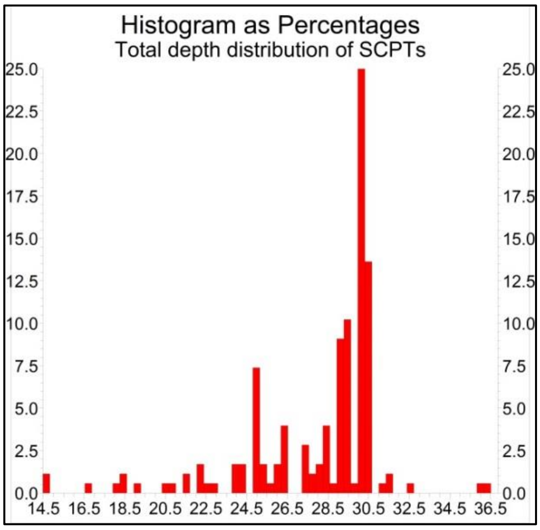

Figure 5.2 Histogram of the total depth distribution of the SCPT's.

5.2 SCPT interpretation

Description of measurement intervals and raw V_s as delivered by consultants and as improved interpretations are included in the database. The V_s data are usually reported to clients in two forms: the raw data by a graphical representation of the shear wave wiggle traces versus measurement depth, and the interpreted V_S versus depth profiles. The picked first arrival times of the raw data are usually not provided. For the surveys of 2014 and thereafter the original shear wave records were available. With the exception of the archive data set until 2014, the data were of sufficient quality to enable reprocessing. The latter data resulted in two sets of V_s profiles: the original contractor-report profiles and profiles reprocessed by Deltares. Both V_s data are stored in the database.

5.3 Re-processing of Seismic CPT’s of Eemskanaal levee

The SCPT’s were performed by Fugro (Nikkels, 2016) using a dual cone, consisting of 2 triaxial geophone sets which are located behind the friction sleeve with a spacing of 0.5 m. The majority of the tests was performed by advancing the cone 1 m after each shear wave velocity test, thus providing intermittent direct and indirect interval measurements. A limited number of SCPT’s were performed by advancing the cone 0.5 m after each shear wave velocity test, enabling a direct measurement over 0.5 m intervals over the whole length of the SCPT.

The draft V_s profiles of Fugro showed anomalously high values in the Pleistocene sands and in some instances zigzag profiles in relatively homogeneous Peelo clays. The Fugro SCPT’s were reprocessed by Deltares (De Lange et al, 2017) using the raw data of the seismic survey. The aim of the reprocessing was to test whether there was a difference in the results of the direct versus the intermittent method. If so, an adjusted workflow to derive reliable Vs profiles from the SCPT measurements would be proposed.

The shear-wave velocities were derived using the SC3RAV software of Baziw Consulting Engineers Ltd using the automatic cross-correlation option, after checking for erratic triggers. The records were separated into sets of true direct interval measurements and true indirect interval measurements of respectively the upper and lower geophone sets. The cross-correlation method was used to determine the arrival times. In the Pleistocene intervals, the direct measurement resulted in a systematically lower velocity than was calculated from the indirectly measured intervals (Figure 5.3).

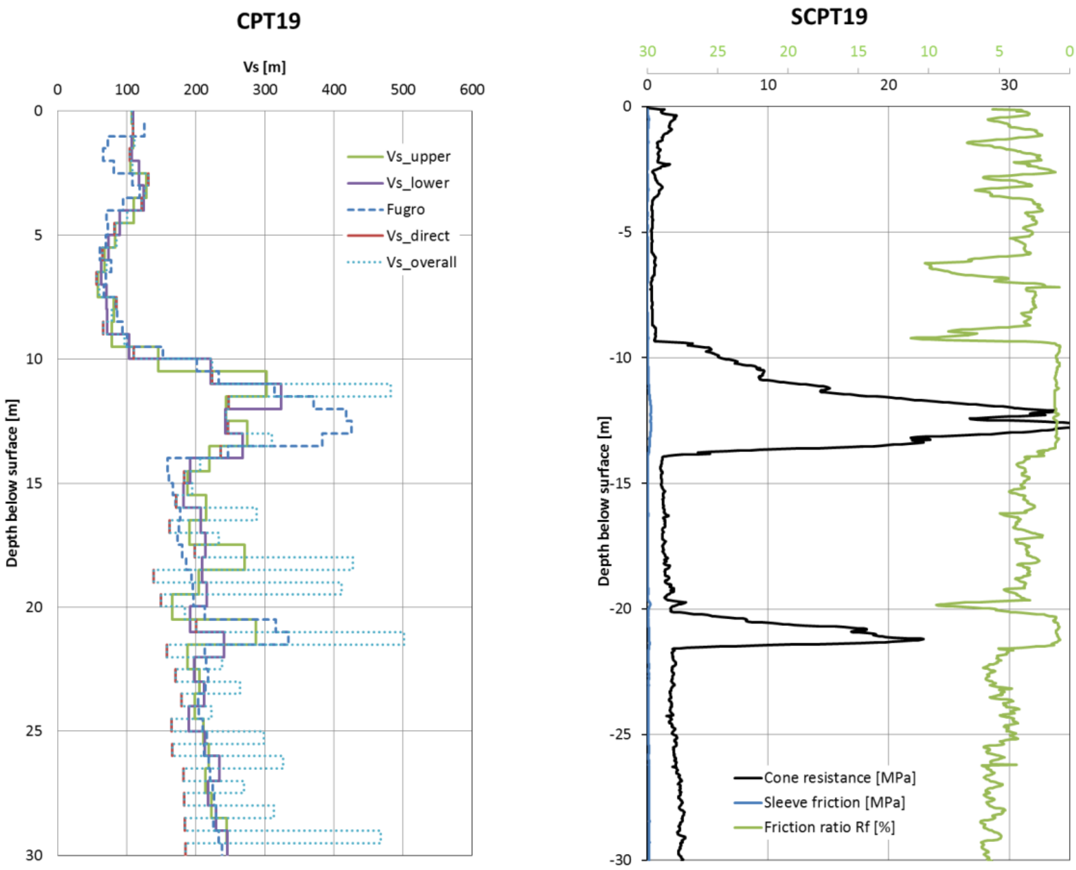

Figure 5.3 Left: V_s interpreted by Fugro and reprocessed V_s by separation of direct (V_s_direct) and pseudo interval travel times (V_s_upper and V_s_lower). Right: corresponding CPT readings indicating relatively homogeneous Pleistocene clay between 14 and 30 m, separated by a sand layer between 20 and 22 m (de Lange et al., 2017).

This phenomenon was observed in several other SCPT's. It is assumed that the discrepancies in the travel times are caused by the disturbance of the soil structure from the penetration of the cone and trailing sensor unit. The diameter of zone of disturbance is related to the consolidation state of the soil, which could be the reason that the discrepancies are limited to the Pleistocene layers.

The final interpretation of the V_S profile was constructed from two parts:

1. For Holocene intervals: V_S derived from combining all travel times (both geophones) (V_s_overall in Figure 5.3, left)
2. For Pleistocene intervals: V_S derived using travel times from the pseudo-intervals of the lower geophone set only.

5.4 Format

The technical format of the tables in the Rockworks® SQLite database storing the SCPT data as shear wave velocities at specific depth intervals (mentioned in Table 5.1) is specified in Table 5.2. The V_s values (in m/s) are stored in the "Point" table in the fields Depth and Value.

Table 5.2 Format of borehole descriptions in Rockworks® database.

RockWorks Table	Fields	Data Description
Location	BhId	Unique numerical id code of a borehole, database key
	Name	Official DINO Borehole name
	Easting	X coordinate in Rijksdriehoekstelsel_New
	Northing	Y coordinate in Rijksdriehoekstelsel_New
	Elevation	Elevation in m. NAP
	TotalDepth	Total depth in m.
	dd_lon	Longitude in WGS84
	dd_lat	Latitude in wgs84
	lcs_x	X coordinate in Rijksdriehoekstelsel_New
	lcs_y	Y coordinate in Rijksdriehoekstelsel_New
PointType	PointTypeId	Unique identification numerical code, database key
	Name	Name of the recorded CPT parameter
	MinValue	Minimum values estimated from the data set
	MaxValue	Maximum values estimated from the data set
	Units	Unit of recorded parameter
Point	PointId	Unique identification numerical code, database key
	BhId	Key referring to the Location table
	PointTypeId	Key referring to the PointType table
	Depth	Depth of the measured value in m. below the surface
	Value	Recorded value of the parameter

6 Borehole logs

6.1 General

KNMI maintains a network of vertical seismic arrays in 200 m deep boreholes. Geophones were installed at 50, 100, 150 and 200 m depth in these boreholes. After drilling of the borehole, and before installation of the geophones, Deltares performed a borehole log in the open borehole. The drilling company considered the borehole walls to be fragile and unstable with a high risk of hole collapse. Due to this risk, Deltares was permitted to lower only one logging instrument into the borehole: either Antares multi-tool or Sonic. The locations of the multi-tool and sonic logs are shown in Figure 6.1.

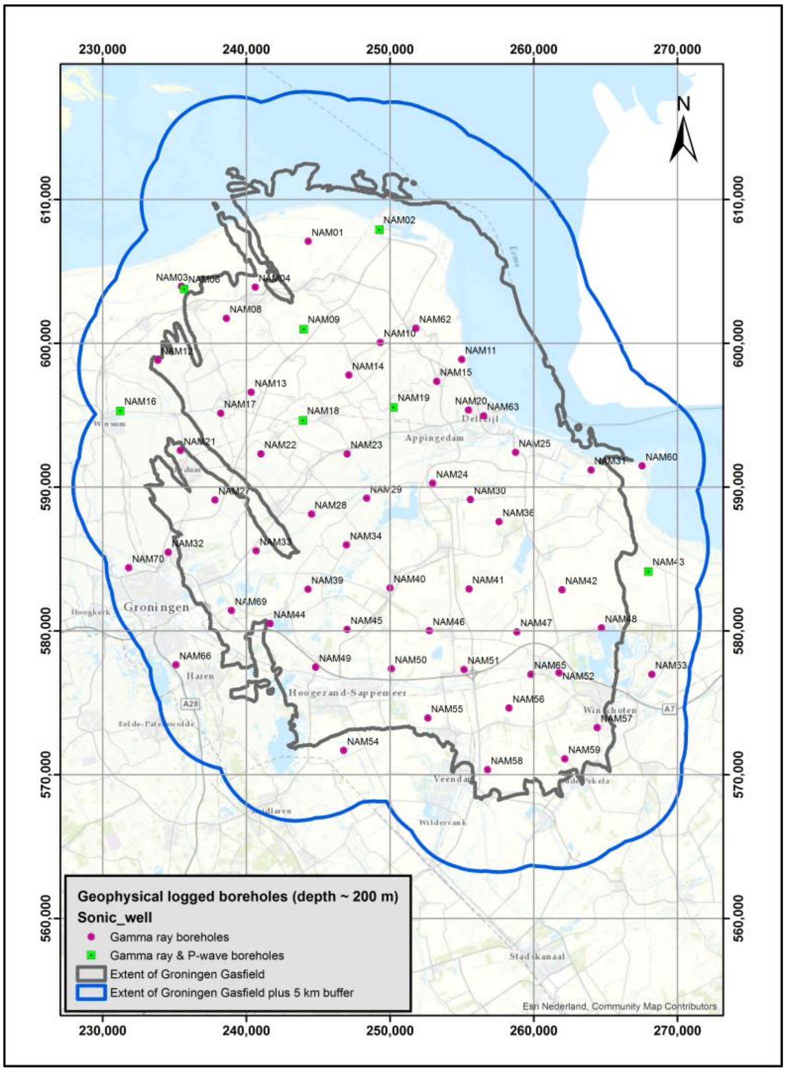

Figure 6.1 Map of borehole locations (n=60) with Multitool logging and P wave recordings (sonic logs).

Multi-tool logging was performed in 53 boreholes. The multi-tool simultaneously measures the natural Gamma radiation, single point resistivity, spontaneous potential, short normal resistivity, long normal resistivity, and temperature. Sonic logging using a P-wave source was performed in 7 of the boreholes. The sonic tool measures the full seismic waveform and natural Gamma radiation. Measurements were not performed in 10 boreholes due to instability of the borehole wall. The interpretation of multi-tool and sonic tool data is extensively described in Doornenbal et al. (2015a) and Doornenbal (2015b) and summarised in sections 6.2.1 and 6.3.1.

6.2 Multi-tool logging

6.2.1 Multi-tool interpretation

The lithology was inferred from the multi-tool data using the Gamma radiation, single point resistivity, short normal and long normal resistivity. In freshwater conditions these four parameters can be used to identify clay layers and differentiate fine sands from coarse sands. However, in the area of interest most groundwater is brackish or even saline. In these conditions, only the Gamma radiation was used for the lithological interpretation, because the resistivity was too much affected by the salinity.

Four lithological units were distinguished, i.e., ‘coarse sand’, ‘medium coarse sand’, ‘fine sand’, and ‘clay’. The Gamma ray classification scheme was created by comparing the measured Gamma radiation in well logs to detailed borehole descriptions of the lithology in the vicinity of the borehole. Peat was not distinguished as a lithological unit, because the Gamma radiation of peat is generally very low and will often be classified as coarse sand. Generally, units of at least ~ 2 m thickness were manually interpreted.

6.2.2 Multi-tool format

The multi-tool geophysical logging equipment records a number of parameters, listed in Table 6.1. The technical format of the tables in the Rockworks® SQLite database storing the Multi-tool logging data is specified in Table 6.2. The derived lithology from the Gamma ray recordings is stored in the “Lithology” table and the Digital Geological Model stratigraphy (TNO-DGM v2.2) is stored in the table “Stratigraphy”. The geophysical parameters as a function of depth are stored in the “Point” table with the keys of the individual parameters in the “PointType” table. The Vp_reliable and Vp_unreliable fields are empty for the multi-tool boreholes.

Table 6.1 List of recorded geophysical parameters by the Multi-tool.

Name of geophysical parameter	Units	Description
BHT_MULTI	Degrees celsius	Borehole Temperature
GR_MULTI	gAPI	Gamma ray in gAPI
GRRaw_MULTI	Counts/sec	Gamma ray as counts/sec
LONO_MULTI	Ohmmeter	Long Normal resistivity
LONO_Spline	Ohmmeter	Long Normal resistivity smoothed by splines
SHONO_MULTI	Ohmmeter	Short Normal resistivity
SHONO_Spline	Ohmmeter	Short Normal resistivity smoothed by splines
SP_MULTI	millivolts	Spontaneous potential
SPR_MULTI	Ohmmeter	Single point resistivity
Vp_reliable	m/sec	P-wave velocity reliable
Vp_unreliable	m/sec	P-wave velocity unreliable

Table 6.2 Format of multi-tool data in Rockworks® database.

RockWorks Table	Fields	Data Description
Location	BhId	Unique numerical id code of a borehole, database key
	Name	Official DINO Borehole name
	Easting	X coordinate in Rijksdriehoekstelsel_New
	Northing	Y coordinate in Rijksdriehoekstelsel_New
	Elevation	Elevation in m. NAP
	TotalDepth	Total depth in m.
	dd_lon	Longitude in WGS84
	dd_lat	Latitude in wgs84
	lcs_x	X coordinate in Rijksdriehoekstelsel_New
	lcs_y	Y coordinate in Rijksdriehoekstelsel_New
LithType	LithTypeId	Unique identification numerical code, database key
	Name	Combination of extended lithology, colour and grainsize class
	Patterns….	Drawing Patterns in RockWorks graphics
	Background	Drawing colours in LongInt numerical format
	Foreground	Drawing colours in LongInt numerical format
	FillPercentage	Width of the lithology columns in graphics
Lithology	BhId	Key referring to the Location table
	Depth1	Top of the lithological layer in m. below the surface
	Depth2	Top of the lithological layer in m. below the surface
	LithTypeId	Key referring to the LithType table
	Comment	Derived main lithology from the Gamma logs
StratType	StratTypeId	Unique identification numerical code, database key
	Name	DINO name of geological formations and layers (2003 Terminology)
	Patterns….	Drawing Patterns in RockWorks graphics
	Background	Drawing colours in LongInt numerical format
	Foreground	Drawing colours in LongInt numerical format
	FillPercentage	Width of the stratigraphy columns in graphics
Stratigraphy	BhId	Key referring to the Location table
	Depth1	Top of the lithological layer in m. below the surface
	Depth2	Top of the lithological layer in m. below the surface
	StratTypeId	Key referring to the StratType table
	Comment	Original RGD Litho-stratigraphy
PointType	PointTypeId	Unique identification numerical code, database key
	Name	Name of the recorded CPT parameter
	MinValue	Minimum values estimated from the data set
	MaxValue	Maximum values estimated from the data set
	Units	Unit of recorded parameter
Point	PointId	Unique identification numerical code, database key
	BhId	Key referring to the Location table
	PointTypeId	Key referring to the PointType table
	Depth	Depth of the measured value in m. below the surface
	Value	Recorded value of the parameter

6.3 Sonic logging

6.3.1 Sonic interpretation

The lithology was inferred using natural Gamma radiation only, similar to the multi-tool interpretation. A correction was applied for the different operation speed of the tool.

Due to the shallow depths and soft sediments, standard processing of the seismic data using picking of first arrivals of the seismic waves was not possible. Instead, the traces from the two receivers in the tool were first filtered to reduce noise. Next, the travel time difference was obtained by cross correlation of the filtered traces. The P-wave velocity was calculated from the fixed distance between the receivers and the travel time from the cross correlation. The top 5 m below the surface were not included due to the high level of noise.

6.3.2 Sonic format

The format of the tables in the Rockworks® SQLite database storing the Sonic data is exactly the same as for the Multi-tool logging data (Table 6.1). The fields of LONO_MULTI, SHONO_MULTI, SP and SPR are empty for the sonic boreholes. The V_P values are stored either in Vp_reliable or in Vp_unreliable. In some cases, no reliable V_P values could be derived from the sonic logs.

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