NAM

Liquefaction sensitivity of the shallow subsurface of Groningen

Deltares and TNO-GSN: Mandy Korff, Ger de Lange, Piet Meijers, Ane Wiersma, Fred Kloosterman

Date November 2016

Editors Jan van Elk & Dirk Doornhof

General Introduction

The ground accelerations experienced as a result of the earthquakes induced by the production of gas from the Groningen field are locally dependent on the shallow geological and soil conditions. This is called the site response effect. NAM has asked Deltares to build a detailed model of the shallow subsurface below Groningen (Ref. 2, 3 and 4). This report prepared by Deltares describes the quarternary geology of the Groningen area. In preparing this model of the shallow subsurface below Groningen, Deltares used of the beta-version of the GEOTOP database of TNO Geologische Dienst Nederland (TNO-NITG) supplemented by more recent data. Additional data collected over the years in support of foundation design and other construction activities was sourced from Fugro and Wiertsema. These are mainly CPT measurements (cone penetrations tests). Additionally, geological data measured in the shallow geophone wells was used.

As an introduction to the quaternary geology of the Groningen area, Erik Meijles of the Rijksuniversiteit Groningen has written a report titled: "De ondergrond van Groningen: een geologische geschiedenis" (Ref. 1).

Apart from ground movement, the potential for liquefaction is also of interest. Existing methods for predicting susceptibility of sands to liquefaction have been reviewed and extended to the characteristics of the induced earthquakes in Groningen (Ref. 5).

The current report makes use of the detailed geological description of the shallow geology and soil conditions to provide insight into the occurrence of sands to be investigated for liquefaction susceptibility.

References

1. De ondergrond van Groningen: een Geologische Geschiedenis, Erik Meijles, April 2015.
2. Geological schematisation of the shallow subsurface of Groningen (For site response to earthquakes for the Groningen gas field) – Part I, Deltares, Pauline Kruiver and Ger de Lange.
3. Geological schematisation of the shallow subsurface of Groningen (For site response to earthquakes for the Groningen gas field) – Part II, Deltares, Pauline Kruiver and Ger de Lange.
4. Geological schematisation of the shallow subsurface of Groningen (For site response to earthquakes for the Groningen gas field) – Part III, Deltares, Pauline Kruiver and Ger de Lange.
5. Unbiased Cyclic Resistance Ratio Relationships for Evaluating Liquefaction Potential in Groningen, Russell Green, Adrian Rodriguez-Marek, Peter Stafford, Julian Bommer, April 2016.

NAM

<table>
<tr><td>Title</td><td colspan="2">Liquefaction sensitivity of the shallow subsurface of Groningen</td><td>Date
Initiator</td><td>November 2016
NAM</td></tr>
<tr><td>Autor(s)</td><td>Deltares and TNO-GSN: Mandy Korff, Ger de Lange, Piet Meijers, Ane Wiersma, Fred Kloosterman</td><td>Editors</td><td colspan="2">Clemens Visser, Jan van Elk
Dirk Doornhof</td></tr>
<tr><td>Organisation</td><td>PanTerra Geoconsultants</td><td>Organisation</td><td colspan="2">NAM</td></tr>
<tr><td>Place in the Study and Data Acquisition Plan</td><td colspan="4"><u>Study Theme:</u> Shallow Geology and Soil Description
<u>Comment:</u>
General Introduction
The ground accelerations experienced as a result of the earthquakes induced by the production of gas from the Groningen field are locally dependent on the shallow geological and soil conditions. This is called the site response effect. NAM has asked Deltares to build a detailed model of the shallow subsurface below Groningen (Ref. 2, 3 and 4). This report prepared by Deltares describes the quarternary geology of the Groningen area. In preparing this model of the shallow subsurface below Groningen, Deltares used of the beta-version of the GEOTOP database of TNO Geologische Dienst Nederland (TNO-NITG) supplemented by more recent data. Additional data collected over the years in support of foundation design and other construction activities was sourced from Fugro and Wiertsema. These are mainly CPT measurements (cone penetrations tests). Additionally, geological data measured in the shallow geophone wells was used.
As an introduction to the quaternary geology of the Groningen area, Erik Meijles of the Rijksuniversiteit Groningen has written a report titled: ”De ondergrond van Groningen: een geologische geschiedenis” (Ref. 1).

Apart from ground movement, the potential for liquefaction is also of interest. Existing methods for predicting susceptibility of sands to liquefaction have been reviewed and extended to the characteristics of the induced earthquakes in Groningen (Ref. 5).

The current report makes use of the detailed geological description of the shallow geology and soil conditions to provide insight into the occurrence of sands to be investigated for liquefaction susceptibility.</td></tr>
<tr><td>Directliy linked research</td><td colspan="4">1. Introductory text: “De ondergrond van Groningen: een geologische geschiedenis” by Erik Meijles of the Rijksuniversiteit Groningen.</td></tr>
</table>

	2. Geological schematisation of the shallow subsurface of Groningen (For site response to earthquakes for the Groningen gas field) 3. Unbiased Cyclic Resistance Ratio Relationships for Evaluating Liquefaction Potential in Groningen
Used data	GEOTOP Beta-version and CPT data sourced through Fugro and Wiertsema.
Associated organisation	Deltares and TNO-GSN
Assurance	NAM

Liquefaction sensitivity of the shallow subsurface of Groningen

Deltares

Liquefaction sensitivity of the shallow subsurface of Groningen

Mandy Korff
Ger de Lange
Piet Meijers
Ane Wiersma
Fred Kloosterman

1209862-005

Deltares

Title
Liquefaction sensitivity of the shallow subsurface of Groningen

Client	Project	Reference	Pages
Nederlandse Aardolie Maatschappij B.V.	1209862-005	1209862-005-GEO-0008-gbh	64

Keywords
Shallow geology, liquefaction, relative density, subsurface model, sensitivity, Groningen

Summary
One of the risk items related to the Groningen earthquakes is related to the occurrence of liquefaction of sand layers, which could potentially lead to loss of strength of the soil and settlements of surface and structures. The shallow subsurface of Groningen, consisting of Holocene and Pleistocene sediments, is heterogeneous, resulting in variations in types of sand and their properties. It is expected that more insight can be obtained in the risk of liquefaction from Groningen-specific information and knowledge of the subsurface.

Deltares has built a geological model for the Groningen field (+ 5 km buffer) for this purpose. This Geological model for Liquefaction in the province of Groningen (GLG) is based on CPTs, the GeoTOP Oostwadden version 1.0 subsurface model (developed by TNO) and various other sources. The GLG-model built by Deltares consists of maps defining the extent of geological units containing sand, a detailed description of the known properties of the sand in these geological units and an analysis on the total and ratio of relative sand densities in these units based on CPTs. This information allows the assessment of which geological units are most susceptible to liquefaction based on their relative density, and where and how deep these potentially susceptible areas occur.

This report describes the method for the construction and the results of the GLG-model based on information collected in 2015 and additional information from the first half of 2016. Quality checks are performed on the model and recommendations are given for future versions. When more data becomes available, updates of the GLG-model are anticipated.

References
Contract UI46802 "Studies on the soil in Groningen"

Version	Date	Author	Initials	Review	Initials	Approval	Initials
1 draft	May 2015	Dr. ir. M. Korff and others		Dr. I. Ritsema		Ing. A.T. Aantjes	
2 final	Sept 2016	Dr. ir. M. Korff and others		Drs. R. Harting, TNO-GSN		Ing. A.T. Aantjes	
3 final	Okt 2016	Dr. ir. M. Korff and others	MK	Drs. R. Harting, TNO-GSN	RH	Ing. A.T. Aantjes	HA

State
final

1209862-005

Deltares

Title
Liquefaction sensitivity of the shallow subsurface of Groningen

Client	Project	Reference	Pages
Nederlandse Aardolie Maatschappij B.V.	1209862-005	1209862-005-GEO-0008-gbh	64

Contents

1 Introduction

1.1 General setting

The motivation for the construction of a **G**eological model for **L**iquefaction in the province of **G**roningen Field (GLG-model) is the need for information on this topic in the Hazard and Risk study of the NAM. The area of interest includes the extent of the Groningen gas field plus a 5 km buffer around it (see Figure 1.1).

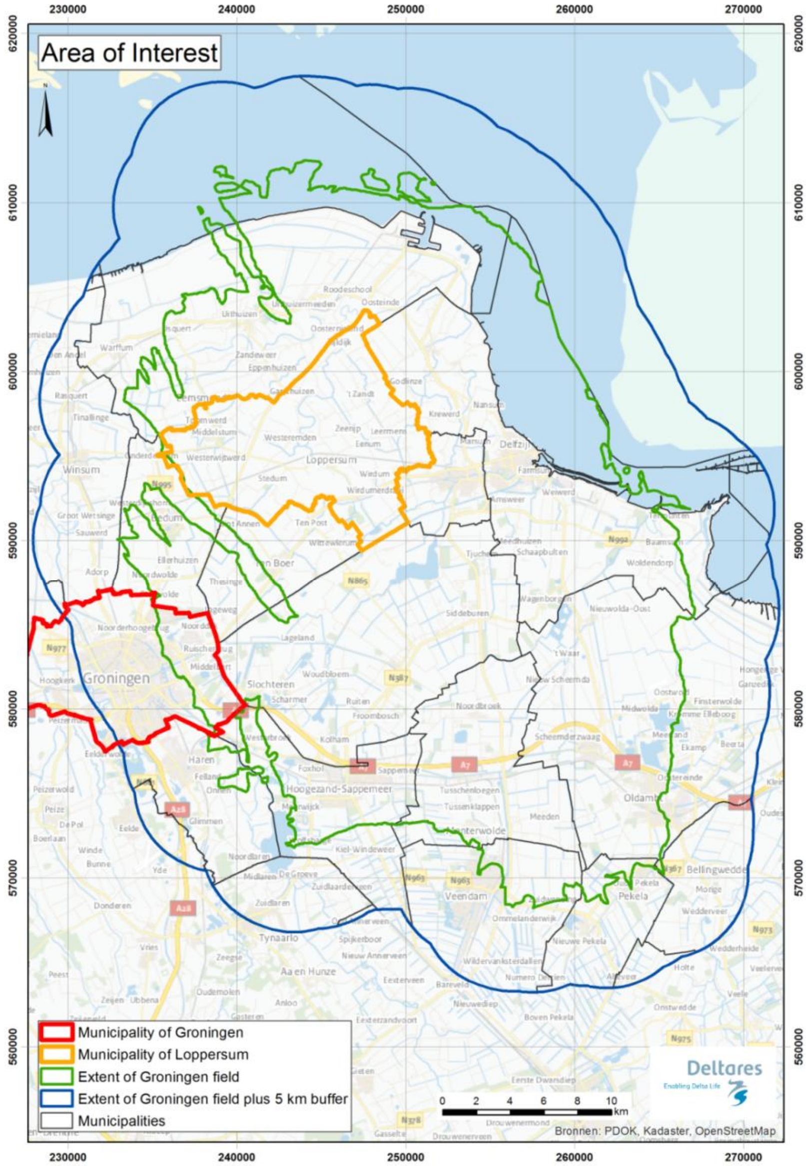

Figure 1.1 Area of interest showing the extent of the Groningen gas field and a 5 km buffer zone

To understand and explain the effects of earthquakes on the surface, for example on structures, the chain of effects is separated into four parts (Figure 1.2):

1. Source effect, such as the type of earthquake, depth of occurrence, duration, magnitude, stress drop, frequency content, orientation.
2. Path effect, describing the decrease in amplitude of seismic waves with distance. Factors that contribute to the path effect are for example geometrical spreading and attenuation.
3. Site response effect: amplification of ground shaking motion due to contrasts in seismic impedance at transitions from stiff to soft layers. The site response to ground shaking caused by earthquakes is referred to as “site response” in the remainder of the report.
4. Soil-structure interaction: response of soils and structures at shaking of the ground, e.g. the response of a building due to an earthquake.

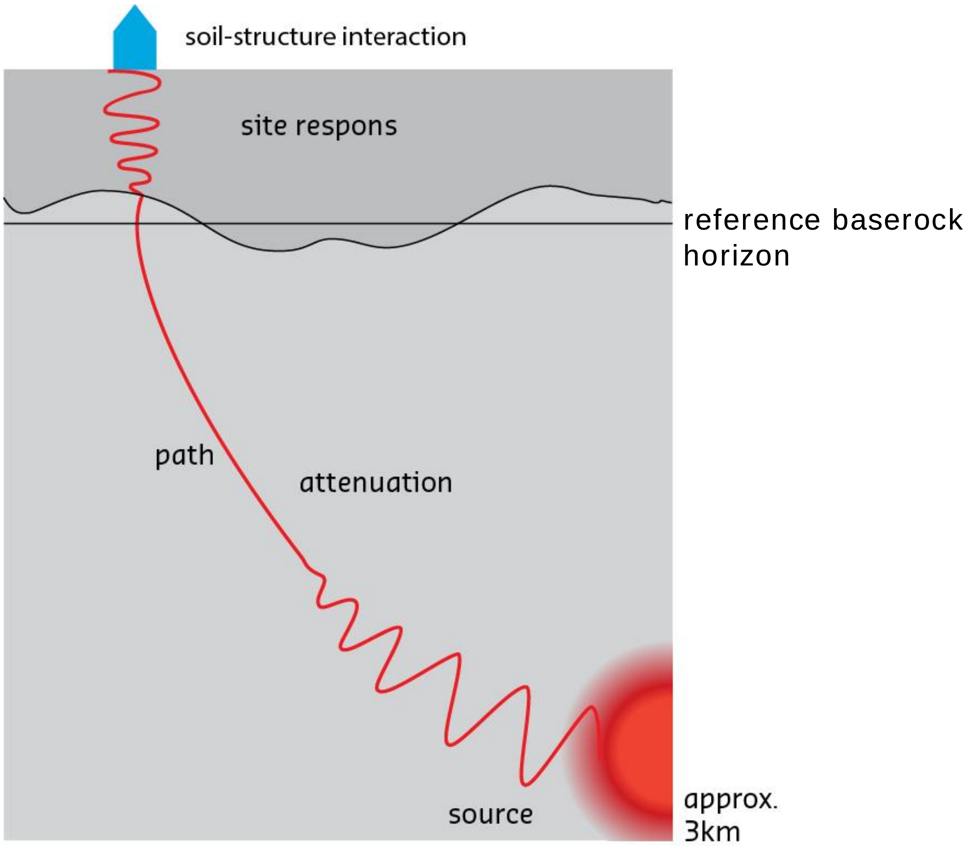

Figure 1.2 Sketch showing the effect of an earthquake on the surface via the route of source, path, site response and soil-structure interaction. The source and path effects act in the deep rock layers, while the site response mainly acts in the top layer of soft sediments

The activities of Deltares for the NAM study program are focussed on the modelling of the response of the shallow subsurface, while others in the research group are concerned with the source and path effects and the response of the structures.

The scope of this report is to provide Groningen-specific data about the sensitivity of the Groningen subsoil for liquefaction in the form of regional maps showing areas with different sensitivity to liquefaction. The calculation of the amount of liquefaction and the risks related to foundations or structures are not part of this study.

In 2015 and 2016, Deltares has constructed version 1 and 2 of a regional geological model of the shallow subsurface of the Groningen field to determine the site amplification effect (GSG-model). The liquefaction sensitivity model builds upon elements from the site response model, but has a specific focus on the occurrence of sand layers, their deposition characteristics and geotechnical aspects related to the probability of liquefaction. In clay and peat the cyclic loading will not truly create a state of liquefaction but rather softening of the clay and peat. It is outside the scope of this report to discuss the potential loss of strength of clay and peat during earthquakes.

1.2 Version 2 of GLG-model

In 2015 the first (draft) version of the GLG-model was presented. This model was based on the available data at that time and a beta version of the GeoTOP model. This model was updated in 2016, based on additional information collected in the first half of 2016, which includes the released v1.0 of the GeoTOP model. This report (v3) presents the updated GLG-model. Compared to the report of September 2016 only the layout of some figures and recommendations has been changed for more clarity. The 2016 model has been used to create maps which present aggregated results with respect to the liquefaction sensitivity, especially related to the density, depth and thickness of the sand deposits in Groningen. Recommendations for future versions of the GLG-model are summarised in chapter 9.

1.3 Readers guide

The report is structured as follows. Chapter 2 describes the background of the general shallow geology of Groningen and its relation to liquefaction by earthquakes. Chapter 3 sums up the available background information used for the construction of the Groningen subsurface model. Chapter 4 reviews the relevant geological units with sand layers. In Chapter 5, the method of estimating relative sand densities from CPTs is given. Chapter 6 describes the distribution of relative sand densities in a variety of maps, while a quality check is given in Chapter 7. Conclusions on the distribution of sand densities are presented in Chapter 8. In Chapter 9, we give recommendations for future developments and updates of the GLG-model.

2 Background

2.1 The liquefaction phenomenon

One of the main geotechnical concerns related to earthquakes is whether the subsurface will liquefy, as liquefaction has been observed in many earthquakes around the world (usually in earthquakes with magnitude Mw=5 and above). When this occurs the soil loses nearly all of its strength and large stability problems with buildings, dikes etc. may occur. It is therefore important to predict the occurrence of liquefaction as accurately as possible. To do this, both the resistance of the subsurface and the loading due to the earthquake play an important role. This report focuses on the liquefaction potential of the subsurface of Groningen; thus the existence of sand layers, their thickness, their depth and geological and geomechanical characteristics which together make up the liquefaction potential.

Liquefaction is mentioned on the USGS website as:
A process by which water-saturated sediment temporarily loses strength and acts as a fluid.

2.2 Factors that determine the liquefaction potential

The liquefaction potential of a specific sand layer is determined by (at least) the following characteristics of the sand itself (for more detail and references see paragraphs 2.2.2 to 2.2.6):

- The density of the sediment, compaction.
- Depositional environment.
- The age of the deposit.
- Overconsolidation of the sand layers (previous overburden or ageing).
- The presence of fines (both cohesive and non-cohesive) / grain size distribution / coefficient of uniformity.
- Cementation.
- Particle shape (sphericity, roundness).

Furthermore the effective stress of the specific sand layers in the subsurface plays an important role, mainly determined by the depth below the surface and the ground water level.

Most of the factors mentioned will influence the CPT values, although not for all of them the exact relationship is known. In this report we use CPT values to determine the liquefaction potential (see Chapter 5), but specific attention has been given to geologically sensible clustering of the CPT values for a more detailed estimation. The reasoning behind the clustering is that, as described below, also some other non-CPT related aspects are involved additionally, in the future more detailed assessments of the liquefaction potential may be based on additional geological aspects.

2.2.1 Compaction/ relative density

One of the most important aspects of the liquefaction potential is the density of the sediment: densely packed sand is less likely to liquefy than loosely packed sand. The cone-tip resistance measured in CPTs can be used as a proxy for the sediment density. Therefore, since CPTs are available in large numbers in The Netherlands, the liquefaction assessment for Groningen can best be based on CPT data.

2.2.2 Effect of age and depositional environment

Youd and Perkins (1978) compiled a table including age and depositional environment for evaluating ground failure susceptibility of various depositional environments (Table 2.1). In general, the table indicates that older deposits show a lower liquefaction potential than young deposits (Gillins, 2012). However, the likelihood that age influences the susceptibility to liquefaction varies, based on the depositional environment of the sediment body. Different depositional environments also show variability in susceptibility to liquefaction. The depositional environments mentioned in the table occurring in the shallow subsurface of Groningen are Estuarine, dunes, Alluvial fan, Glacial till, Lacustrine and (Pleistocene) river channels. All of these environments, except for glacial till, show a moderate to high susceptibility to liquefaction.

Type of Deposit	General Distribution of Cohesionless sediments in deposits	Likelihood that Cohesionless Sediments, When Saturated, Would be Susceptible to Liquefaction (by Age of Deposit)			
		<500 yr	Holocene	Pleistocene	Pre-Pleistocene
(1)	(2)	(3)	(4)	(5)	(6)
(a) Continental Deposits					
River Channel	Locally Variable	Very High	High	Low	Very Low
Floodplain	Locally Variable	High	Moderate	Low	Very Low
Alluvial Fan and Plain	Widespread	Moderate	Low	Low	Very Low
MarineTerraces/ Plains	Widespread	-----	Low	Very Low	Very Low
Delta and Fan-delta	Widespread	High	Moderate	Low	Very Low
Lacustrine and Playa	Variable	High	Moderate	Low	Very Low
Colluvium	Variable	High	Moderate	Low	Very Low
Talus	Widespread	Low	Low	Very Low	Very Low
Dunes	Widespread	High	Moderate	Low	Very Low
Loess	Variable	High	High	High	Unknown
Glacial Till	Variable	Low	Low	Very Low	Very Low
Tuft	Rare	Low	Low	Very Low	Very Low
Tephra	Widespread	High	High	?	?
Residual Soils	Rare	Low	Low	Very Low	Very Low
Sebkha	Locally Variable	High	Moderate	Low	Very Low
(b) Coastal Zone					
Delta	Widespread	Very High	High	Low	Very Low
Esturine	Locally Variable	High	Moderate	Low	Very Low
Beach					
High Wave Energy	Widespread	Moderate	Low	Very Low	Very Low
Low Wave Energy	Widespread	High	Moderate	Low	Very Low
Lagoonal	Locally Variable	High	Moderate	Low	Very Low
Fore Shore	Locally Variable	High	Moderate	Low	Very Low
(c) Artificial					
Uncompacted Fill	Variable	Very High	-----	-----	-----
Compacted Fill	Variable	Low	-----	-----	-----

Table 2.1 Effect age on liquefaction potential, Gillis (2012), after Youd Perkins (1978)

Gassman et al (2004) and Leon et al (2006) investigated the effect of ageing for a site in South Carolina. Their conclusion is that the old sediments in the South Carolina Coastal Plain have a 1.6 times higher resistance to liquefaction compared to younger deposits. This result is based on a combination of literature data about the effect of ageing on the cone resistance and the liquefaction potential.

Similarly, Arango and Kramer (1994) show an increase in the liquefaction resistance for older sediments (Figure 2.1).

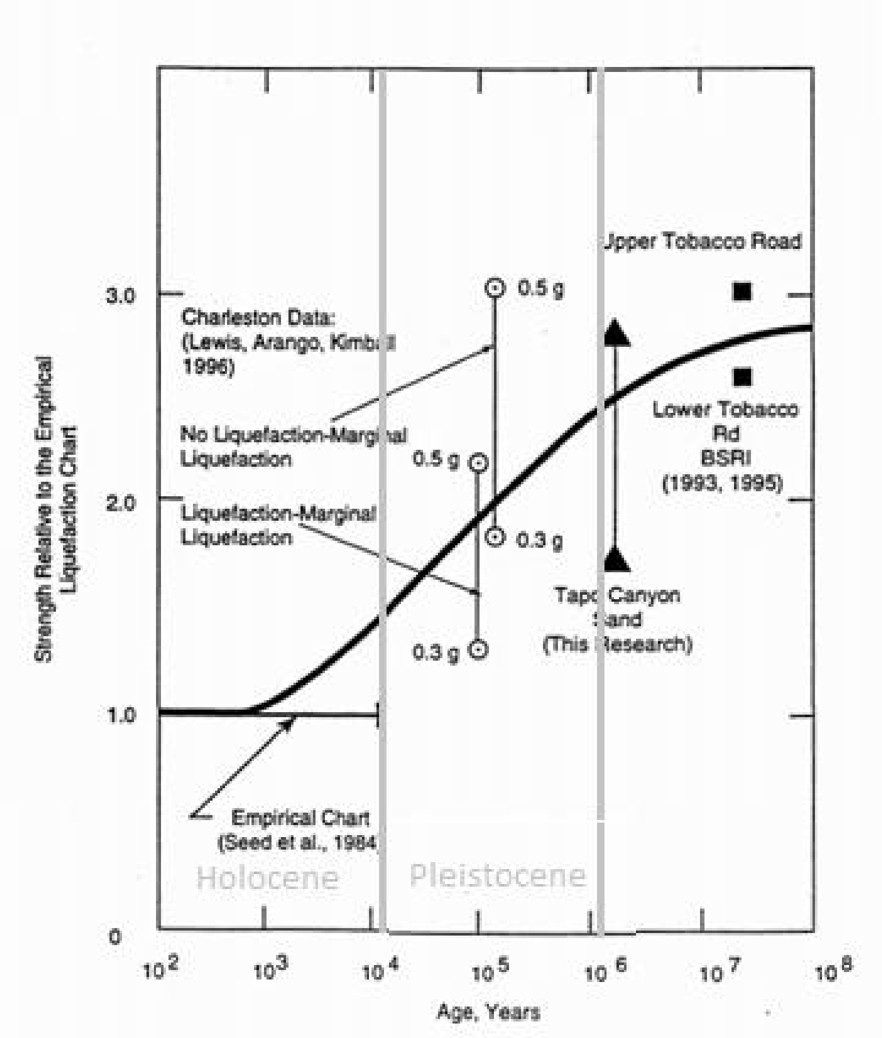

Figure 2.1 Effect age of deposit on liquefaction resistance, from Arango and Kramer (1994). Grey lines indicate the Holocene (12 ka) and Pleistocene (1.6 Ma) period ranges

The Holocene deposits in Groningen date roughly between 0 and 12 thousand years. The age of the Pleistocene deposits ranges from 12 thousand years to 1.6 million years. According to Figure 2.1 the expected increase in liquefaction resistance may be a factor of 1.2 to 2. However, the correlations depicted in this graph are not necessarily representative for the Groningen situation, as Groningen has a different geological history.

The cause of the influence of age is expected to be cementation and/or soil formation in the sediments. Some of these factors are expected to be reflected in the cone-tip resistance values. This topic is currently under investigation. For this report the occurrence of the depositional environments in the Groningen subsurface and the age of the deposits is discussed in detail in Appendix A, which in future may be used to distinguish the liquefaction susceptibility between the different formations.

2.2.3 Effect of overconsolidation

In Groningen, sediments of greater age (pre Saalian: before 240ka ago) may be overconsolidated due to ice sheet loading. This may influence the geomechanical behaviour of these sediments, but also the interpretation of the sediment parameters from e.g. CPT results.

It seems that heavy loading during the Saalian glaciation caused compaction of the sand layers underneath the ice. Analyses of cone penetration test results indicate that sand intervals with high CPT values mainly occur directly underneath glacial tills in a 2 to 5 m thick interval. A cone-tip resistance of over 50 MPa is reached in two types of sand: (1) very coarse intervals within the Drente Formation, Urk Formation and Peelo Formation, and (2) fine sands of the Peelo Formation and Urk Formation. These formations indeed date to a pre-saalien age, details of these formations will be discussed in Appendix A.

Peels and Dijkstra (2010) discuss this aspect: Overconsolidated sands are characterised by a high cone resistance (20 to 60 MPa) and a high friction rate (1 to 2.5%). The horizontal stress may be 1 to 3 times the vertical stress. The horizontal stress is sensitive to vibrations and found to reduce to the value for normally consolidated sand when vibrated.

In overconsolidated sand (or horizontally forced sand/lateral moraine) the horizontal stress becomes larger and for sand with the same (relative) density the cone resistance increases. Conversely, this implies that for sand with the same cone resistance in overconsolidated sand the relative density is lower. This will result in an increased liquefaction potential. On the other hand overconsolidation is expected to increase the liquefaction resistance.

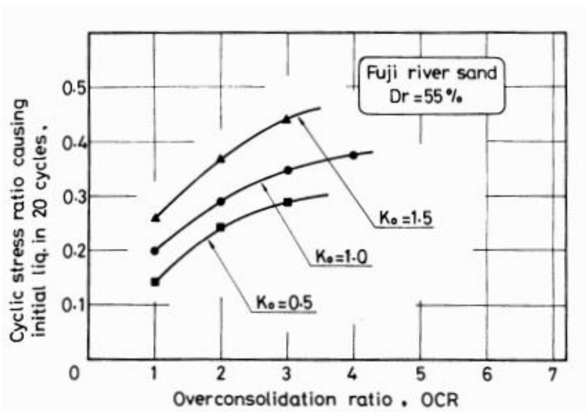

Figure 2.2 Effect of overconsolidation on liquefaction resistance, from Ishihara and Takatsu (1978)

From the above it follows that it is not clear if in overconsolidated sands the use of correlations for normally consolidated sands is conservative or optimistic. As overconsolidated sands are also older sands (see section 2.2.2 for the effect of ageing) both aspects need to be considered. In the descriptions of the geological units present in the subsurface of Groningen, we indicate whether the deposits have been exposed to ice-sheet loading.

2.2.4 Particle shape

Sphericity or its opposite term angularity of sand grains may be a factor that has an influence on the susceptibility to liquefaction. However, within the TopIntegraal study (Bosch et al., 2014), 97% of all described sand layers have been marked as moderately rounded. The classes rounded (2%) and angular (1%) are insignificant compared to the moderately rounded class. Therefore, within the units taken into account in this study, no effects of the roundness of sand on the liquefaction potential are expected.

2.2.5 Cementation

In the core descriptions within the TopIntegraal study (Bosch et al., 2014), cementation is mainly related to interstitial secondary minerals precipitated from pore waters involving iron hydro-oxides, carbonates involving Ca and Fe and silica. There seems to be no relation to stratigraphic units or lithofacies, but cementation is expected to be correlated with age: the higher the age, the more cementation may have taken place.

2.2.6 Grain-size distribution

Grain size is often suggested to be a criterion for liquefaction susceptibility. Mostly a graph from Tsuchida, is used (see e.g. Ishihara (1985). Other parameters that may influence the liquefaction susceptibility are the fines content (<63 µm) and the uniformity coefficient (calculated as the d60/d10 percentiles of the sand fraction (63µm - 2000 µm). However, no convincing relations have been published so far in the literature. To accommodate future application of grain sizes in the liquefaction studies in Groningen, Appendix A contains statistical data (median values) of important lithological parameters of sediments from the shallow subsurface of Groningen.

3 Sources of information

3.1 Overview of sources

For the liquefaction sensitivity assessment, several sources of information have been used. Close cooperation between Deltares and TNO-GDN (Geological Survey of the Netherlands) facilitated the use of state-of-the-art products in the project. The various sources of information with their short descriptions are listed in Table 3.1.

Dataset	Short description
Borehole records	Boreholes extracted from the TNO/GSN DINO-database
TopIntegraal	A drilling and sampling campaign launched in 2006 in order to obtain sediment samples on a national scale to determine the physical and geochemical properties of the Dutch shallow subsurface. The data and their interpretations are a unique national database, and will be the basis of a 3D property model of the Netherlands.
CPT	Cone Penetration Test, measuring cone-tip resistance and sleeve resistance upon pushing the probe into the soil. CPTs were obtained from the DINO database and at a later stage from Fugro and Wiertsema en Partners (through NAM).
GeoTOP	GeoTOP is a 3D model of the subsurface containing voxels (volume cells) of 100 m x 100 m and 0.5 m thickness. Each voxel contains geological (lithostratigraphical) unit, lithological class and (in the future) various physical and chemical properties as attribute. The depth range of GeoTOP is from the surface to maximum of 50 m- NAP. Currently, GeoTOP is constructed for the entire Netherlands. A description of GeoTOP Oostelijke Wadden is given in the GSG report (Kruiver et al., 2015).

Table 3.1 Sources of subsurface information available for schematisation

3.2 Borehole records

An important source of subsurface information consists of borehole records from the DINO-database. Seventy-five of these boreholes were carried out for the drilling campaign of the TopIntegraal project, which aims to collect high quality samples of the Dutch subsurface and subsequently analyse them for a wide range of physical and chemical properties. The boreholes themselves are of high quality with detailed lithological descriptions. In this report, the sedimentary characteristics discussed in Chapter 4 and Appendix A are derived from a recent report describing the results from the TopIntegraal drilling campaign and laboratory analyses in the Northern Netherlands (Bosch et al., 2014). However, of the 75 boreholes used in the TopIntegraal study, only 12 are actually situated within the Groningen area.

3.3 CPT records

Cone penetration test (CPT) data have been collected from three major sources, namely: TNO-DINO database, Fugro and Wiertsema. The total number of CPT locations amounts to 5732.

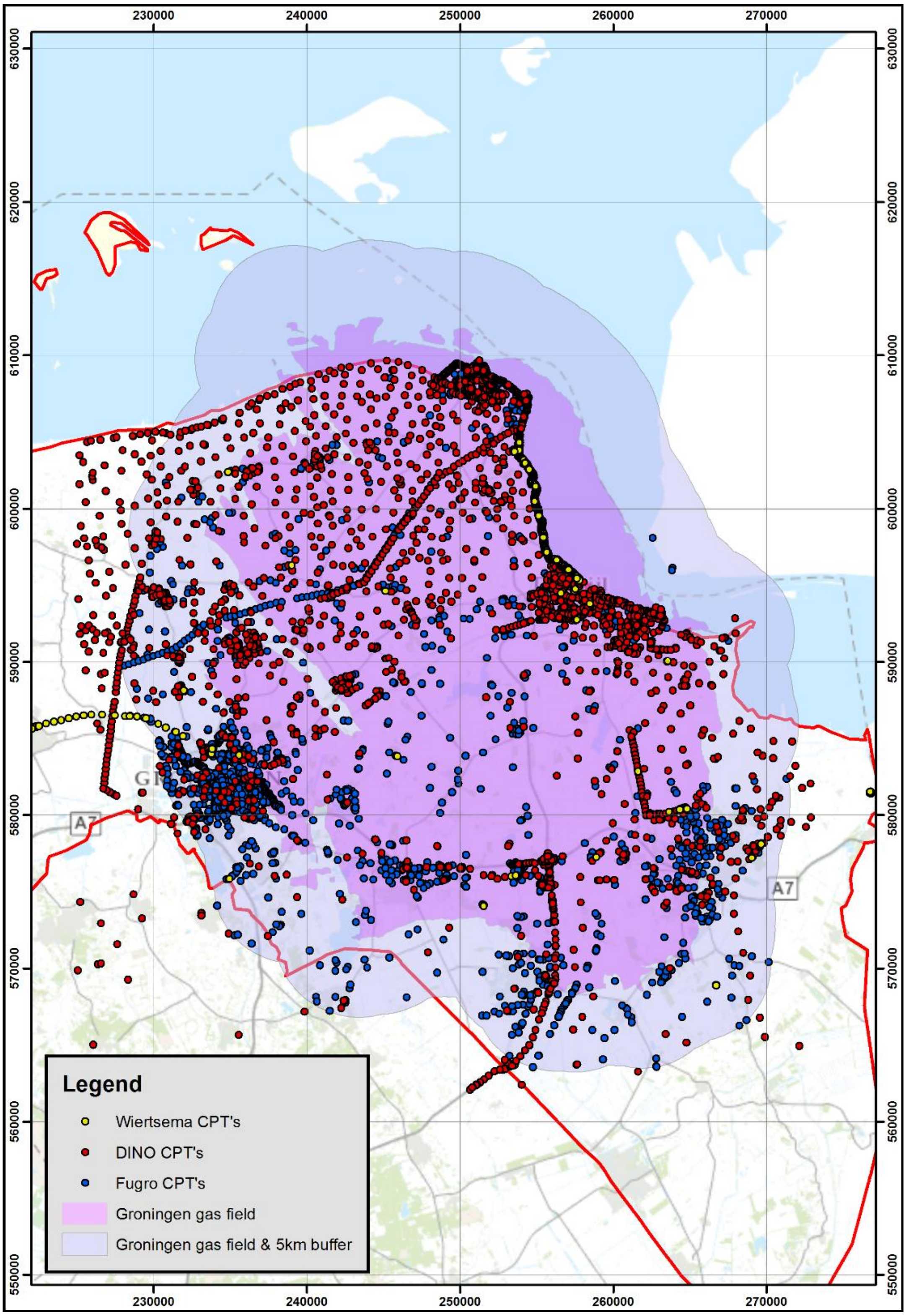

Figure 3.1 Locations of the 5732 collected CPTs in Groningen

The map in Figure 3.1 shows the distribution of the CPT locations in the province of Groningen in and around the NAM gas field. The CPTs are not evenly distributed over the project area: dense populations can be found along canals and (projected) civil works. The same applies to a lesser extent to the CPTs concentrated in the urban areas of Groningen city and Delfzijl. Areas sparse in CPT locations are to be found approximately between Groningen city and Nieuwolda.

In addition, the total depth of the CPTs varies considerably between a few meters and the deepest ones reaching to 70 m. The histogram in Figure 3.2 shows the probability density of the end depths. The standard depths of CPT's are 15, 20, 25 and 30 meters, with a mean depth of about 20 meters.

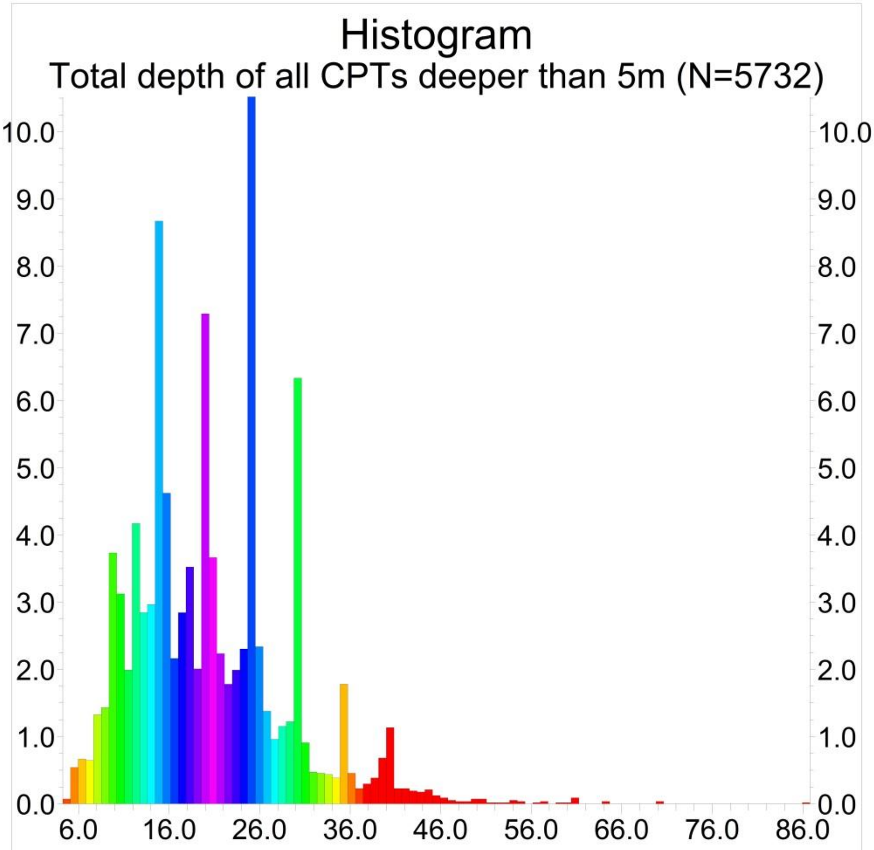

Figure 3.2 Histogram and statistics of the CPT total depth distribution

All used CPTs contain data on cone tip resistance (Qc), sleeve friction (fs) (both recorded in MPa) and the derived Friction Ratio (Rf) expressed in percentages. Practically in all CPTs the recordings are made at depth intervals of 2 cm, 100 CPTs have 1 cm intervals and 25 have 0.5 cm intervals. The data have been screened for outliers and erroneous data. Friction factor values exceeding 10 % have been removed as these outliers often occur at shallow depths of a test. The data from Fugro and Wiertsema were received in the form of ASCII files in the so-called GEF formats, while the DINO-data were obtained from the TNO-DINO database (www.dinoloket.nl) in GEF format. The Dino CPT data consist of source data of variable quality, and a large part has been digitized from older analogue recordings. Quite some DINO CPT data lack cone tip or sleeve friction recordings, often also with much missing data, hampering the interpretation of lithology. These CPT data have been removed from the set that has been analysed. The remaining Fugro and Wiertsema CPT data on the other hand is consistent as it has been recorded digitally.

3.4 GeoTOP

To make a liquefaction model that can be used to predict the sensitivity to liquefaction at a certain location and a depth range, it is necessary to cluster the data into sensible units. The sensitivity to liquefaction is likely related to the properties and age of the sediments. Also, geological units are, amongst others, often distinguished on properties and age. Therefore, in this case we use geological units with similar properties and age to cluster the data of the CPTs. The geological units used in this study originate from the GeoTOP subsurface model.

GeoTOP is the latest generation of 3D subsurface models produced by TNO – Geological Survey of the Netherlands. The model schematizes the shallow subsurface of the onshore part of the Netherlands in millions of voxels, each measuring 100 by 100 by 0.5 m (x, y, z) up to a depth of 50 m -NAP (Stafleu et al., 2011, 2012). Each voxel in the model contains information about the modelled geological unit, the most probable lithological class (including three grain-size classes for sand) and the probability of occurrence for each of these in total 7 lithological classes. The modelled units are based on geological formations defined in the subsurface. Since our analysis is performed on the modelled units we use the term *unit* instead of formation, unless we discuss the physical sediments in a geological formation.

The GeoTOP model is constructed in model areas that roughly correspond to the Dutch provinces. The model area that covers the Groningen gas field (+5 km buffer) is called "Oostelijke Wadden" and has been released early 2016. A general description of GeoTOP Oostelijke Wadden and how the model is constructed is provided in the GSG report (Kruiver et al., 2015).

For this report, the raster files that define the top and base of the modelled geological units that are considered relevant for liquefaction are used. Their relevance is determined based on their composition and depth range. These model units are at least partly composed of sandy deposits and CPTs contain data in the depth range of the units. In addition, the accumulated sand thickness per grid cell for each model unit is used as a cross check for the liquefaction maps (see Chapter 7). The sandier parts of these model units are more susceptible to liquefaction than less sandy parts.

Important aspects of these formations will be described in Chapter 4. More details are given in Annex A.

3.5 Knowledge gaps and future improvements

For the construction of the GeoTOP model, no CPT records are used. The CPT records do provide a valuable source of subsurface information, especially in the depth range between 10 and 30 meters below the land surface where the density of borehole information is much lower and many CPTs records are available. Because no CPT records are used for the construction of the GeoTOP model, the model layers of the top and the base of the model units that we use in this study to group CPT cone-tip resistance can be expected to deviate from the top and the base of the actual geological unit as recorded in the CPT. The consequence would be that cone tip resistance actually belonging to one geological unit may be assigned to another. Using CPTs in the construction of the GeoTOP model could improve the model significantly.

4 Description of the relevant sand layers

For this project, six geological units have been identified to be potentially relevant for the occurrence of liquefaction in Groningen. For each of these sandy units a detailed lithological description is given in Annex A.

The selected formations are:

Holocene age:
- Naaldwijk Formation (Marine tidal deposits).

Pleistocene age:
- Boxtel Formation (periglacial aeolian and local fluvial deposits).
- Eem Formation (Marine tidal deposits).
- Drente Formation, Schaarsbergen Member (Fluvioglacial deposits).
- Urk Formation, Tynje Member (Fluvial and marine tidal deposits).
- Peelo Formation (Glacial outbreak deposits).

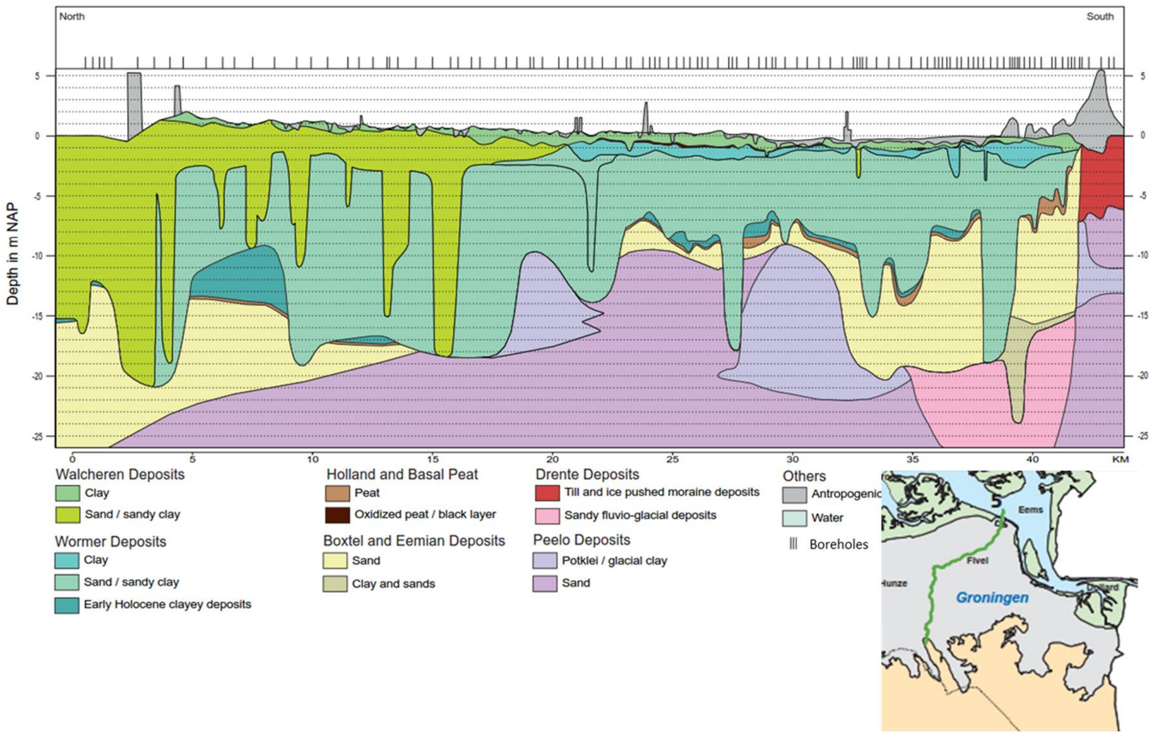

Figure 4.1 North – South geological cross section from the city of Groningen to Eemshaven. The Naaldwijk Formation is a combination of the Wormer- and Walcheren deposits (from: Vos, 2015). The Urk Formation is found locally between the Drente and Peelo Formation

Within these formations, different lithofacies are characterized. A lithofacies unit is a group of sediment with either more or less similar lithological characteristics or a specific variation in them which makes them identifiable in an undisturbed core. The names are descriptive of a depositional environment that may be associated with the lithofacies, it wasn’t necessarily deposited in one.

The following summary of lithological characteristics based on the visual core descriptions focusses on characteristics of sandy intervals and lithofacies that are or could be important for the assessment of the liquefaction potential (see paragraph 2.2). Each of the characteristics potentially influencing the liquefaction potential is discussed per geological unit in the paragraphs below. For the descriptions of parameters such as the sand median class, the NEN 5104 standard is used. The most important definitions are discussed in Appendix A.
Figure 4.2 provides an overview of the relative stratigraphic position of the considered geological units, their age and their depositional environment. It shows that the study area has undergone changes from a glacial environment with ice sheets, to fluvial landscapes and marine conditions to the current terrestrial setting. The oldest deposits considered here are about half a million years old. For further reading about the geology of the Netherlands and stratigraphy of the Netherlands, we suggest Mulder et al. (2003) and Weerts et al. (2000).

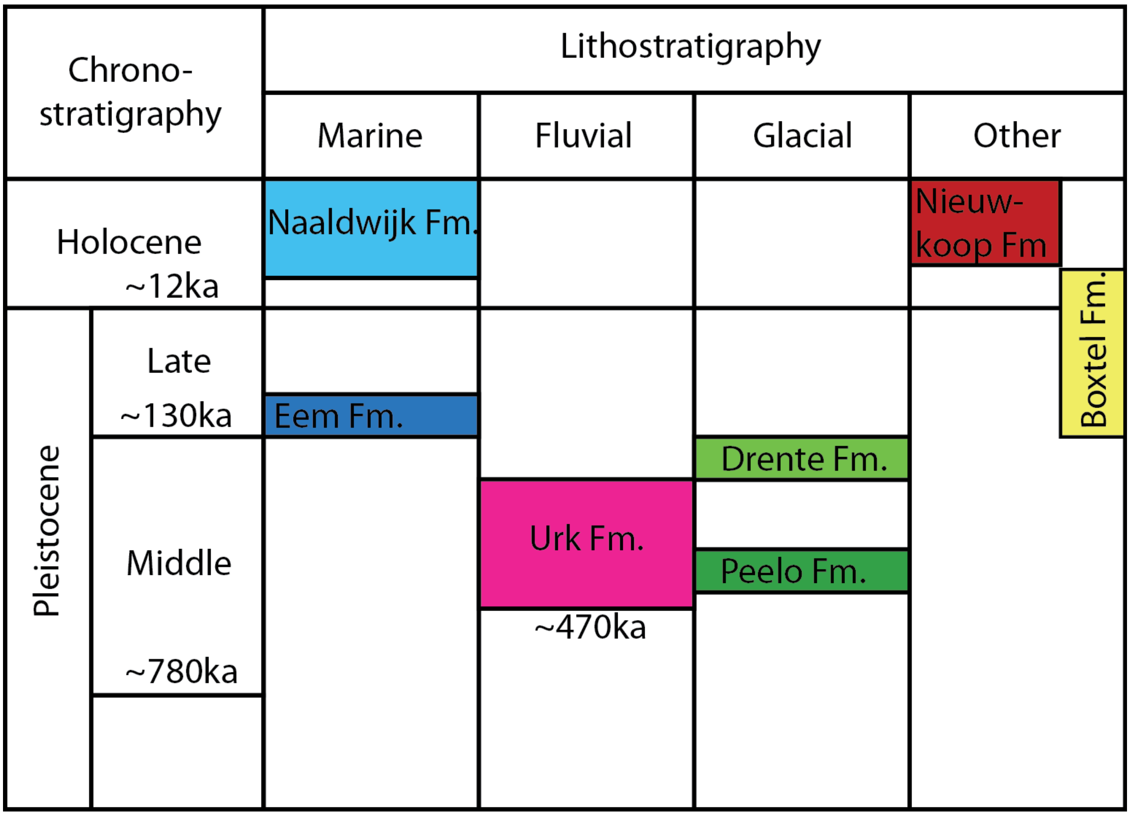

Figure 4.2 Overview of the stratigraphy and time of the considered geological units in Groningen and their depositional environment. The Nieuwkoop Formation consists entirely of peat, and is indicated because it is intercalated with the Naaldwijk Formation

4.1 Naaldwijk Formation

The Naaldwijk Formation consists of marine tidal deposits. It was formed during the Holocene (the current warm period), as sea level rise drowned the Pleistocene lows and formed a marine tidal environment. In this environment, tidal channels, tidal flats, lagoons and salt marshes developed. The formation occurs mainly in the northern half of the study area, in which it reaches a maximum thickness of approximately 28 meters (Figure 4.3). The northern part is thickest and has the highest occurrence of tidal channel deposits, leading to a higher sand content in the formation. In the southern part, tidal flat and salt marsh deposits dominate, resulting in higher clay content.

The Naaldwijk Formation is the youngest of the sandy geological units discussed here. Based on both its young age and depositional environment, the sandy parts in this formation could be particularly susceptible to liquefaction. The sands have not been cemented and have not been exposed to ice-sheet loading.

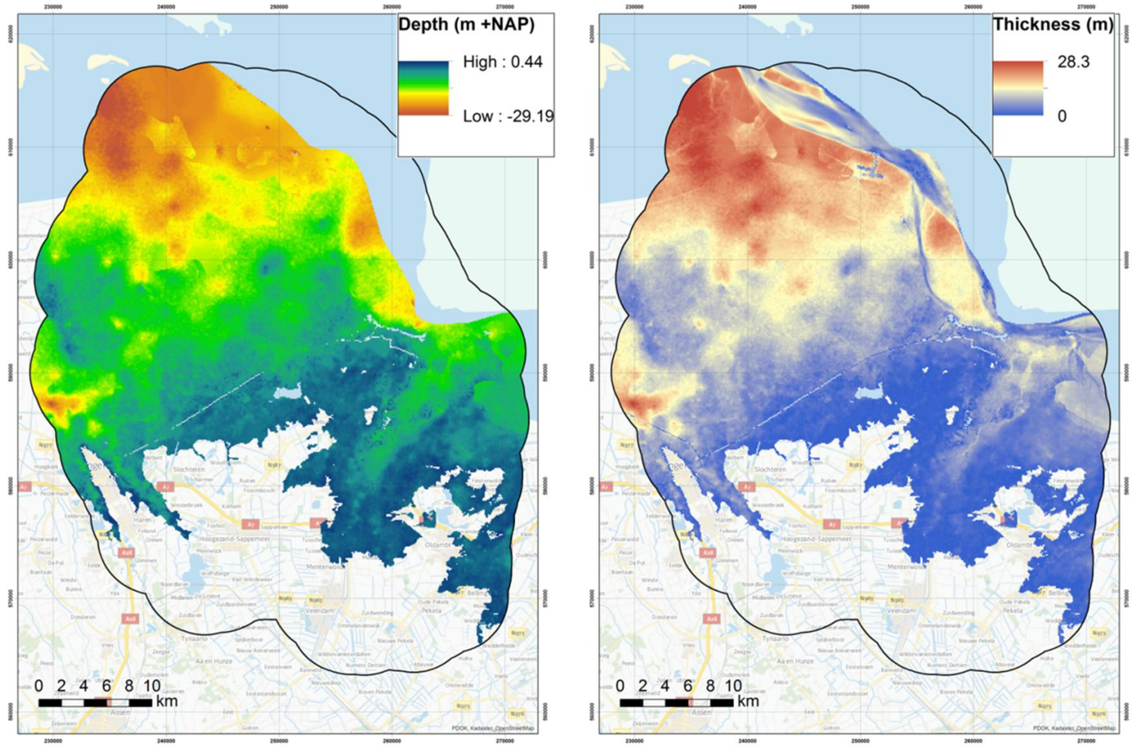

Figure 4.3. Depth of the base (left) and total thickness (right) of the Naaldwijk model unit in the GeoTOP 3D model of the subsurface (Maljers et al., 2016)

Lithofacies that have been distinguished in the Naaldwijk Formation which contain relevant amounts of sand are:

- Tidal channel deposits (fine and medium sand).
- Tidal flat deposits (fine sand, clay and loam).

The tidal channel deposits consist mainly of sand (90%). The remaining material consists of clay, and occasionally loam and shell layers occur. The sand median class varies from SVF to SMF. The sand is moderately rounded, calcareous and contains at least traces of shells and glauconite grains. The deposit is often bedded with either clay or detritus beds.
Tidal flats in the Naaldwijk Formation have a different sand to clay ratio than the tidal channel deposits as they consist of approximately 60% sand and 40% clay layers. All sand layers consist of very fine sand, and are often bedded with clay and detritus beds. The sand is moderately rounded, is calcareous and contains mica, traces of glauconite and traces of shells.

4.2 Boxtel Formation

The Boxtel Formation makes up most of shallow sands in the southern part of the study area. It consists of several types of deposits, associated with aeolian deposition, slopes, small rivers and brooks, lacustrine environments and marshes. In the northern Netherlands, the deposits have a late Saalian to Holocene age (~140ka – 11ka), deposited after the retreat of the Saalian ice sheet until present day in the case of land dunes (Kootwijk Mb.). The sediments have not been exposed to ice sheet loading due to the lack of ice cover in the area during the last ice-age (Weichselian). However, the presence of permafrost during that time has caused extensive cryoturbation, often in sediments belonging to the Boxtel Formation. The upper part of the formation is often formed by the Wierden Member, encompassing aeolian cover sands deposited during the late Pleistocene (older than 11.000 years). Based on depositional environment and possibly their age, they could be susceptible to liquefaction although soil formation is often found in the top of the Wierden member, which generally results in higher resistance.

Types of deposits that have been distinguished in the Boxtel Formation which contain amounts of sand potentially relevant for liquefaction are:
- Dry aeolian deposits.
- Wet aeolian deposits.
- Channel deposits.
- Bank and crevasse deposits.
- Bedded lake and abandoned channel deposits.
- Slope deposits.

The distinct differences between these “lithofacies” are discussed in Annex A. The lithofacies are very local and difficult to map within the Boxtel Formation and are grouped here as Boxtel *undifferentiated* for practical reasons.
The thickest occurrences of the formation are in the old Saalian erosional channels, primarily the Hunze valley and connected lows, as well as in the area around Delfzijl. It can reach a thickness of up to 42 m (Figure 4.4).

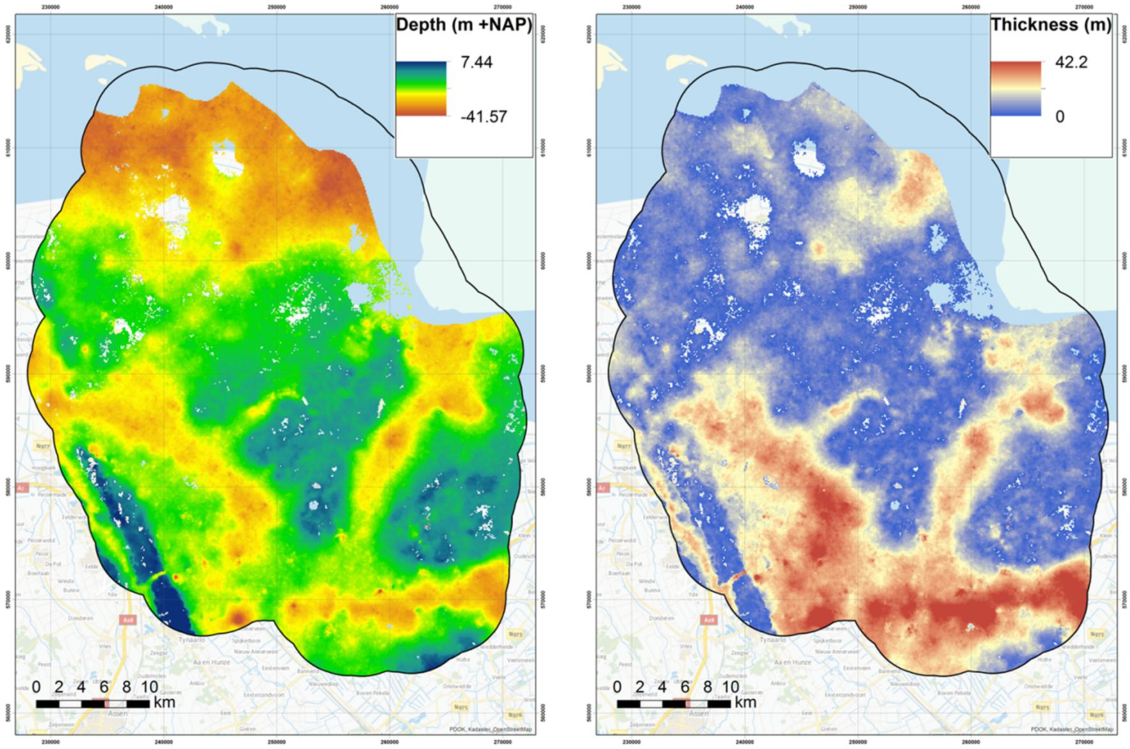

Figure 4.4 Depth of the base (left) and total thickness (right) of the Boxtel model unit (undifferentiated) in the GeoTOP 3D subsurface model (Maljers et al., 2016)

The dry aeolian deposits of the Wierden Member consist of non-calcareous, highly uniform very fine sands. Their thickness varies from 0 to 7, and the fraction of silt and clay very low. The sediments in this member have been deposited at the end of the last glacial and could, based on their age, be susceptible to liquefaction.

Moreover, the Boxtel Formation consists of wet aeolian deposits, channel deposits, bank and crevasse deposits, bedded lake and abandoned channel deposits and slope deposits. The wet aeolian deposits are similar to the dry Aeolian deposits of the Wierden member described above. The difference is that the very fine wet aeolian sands contain loam beds (10%).

The fluvial channel deposits consist of highly calcareous slightly silty sand, in the categories very fine to very coarse. There is some bedding present consisting of detritus and loam. Almost no clay is present in the channel deposits. The bank and crevasse deposits consist mainly of sand. The sand is non-calcareous, very fine to medium fine and slightly silty. Finally, the fluvial layered lake and abandoned channel deposits consist mainly of sand, but also loam and clay beds are present. Some beds of peat are present in this type of deposit. The sand is very fine to very coarse, and can contain high silt and clay fractions. The slope deposits of the Boxtel Formation consist of sand and loam. The non-calcareous sand is very fine to medium fine, and can contain gravel.
All these deposits can occur very locally, and are therefore very difficult to map or predict. Therefore in this study the Boxtel formation is considered as one complex unit.

4.3 Eem Formation

During the Saalian glaciation, ice movement in a north-north-west to south-south-east direction has eroded a depression of several kilometers wide and tens of meters deep; the Hunze valley. At the beginning of the Eemian Interglacial (~126kyr – 116kyr), the valley was partly filled with fluvioglacial and periglacial deposits. However, as a result of sea-level rise, the sea flooded the land and a large tidal area developed in the valley. Ice sheets of the following ice age did not reach the Netherlands, and therefore the sediments of the Eem Formation are not overconsolidated by ice-load. The deposits are comparable to those of the Naaldwijk Formation, but are older.

Two out of three lithofacies distinguished within the Eem Formation have a significant amount of sand:

- Tidal channel deposits (fine, medium and coarse sand, clay).
- Tidal flat deposits (fine sand, clay, loam).

Tidal channel deposits can reach a thickness of over 30 m (Figure 4.5). The channels are filled with bedded sand, often intercalated with organic and clay layers. The sand is mainly slightly silty calcareous sand of the very fine category to medium fine category.

The tidal flat deposits consist of bedded clays and sands. The sand is mainly very fine sand with admixed silt and clay. However, the thickness of the individual layers doesn't exceed more than several tens of centimeters.

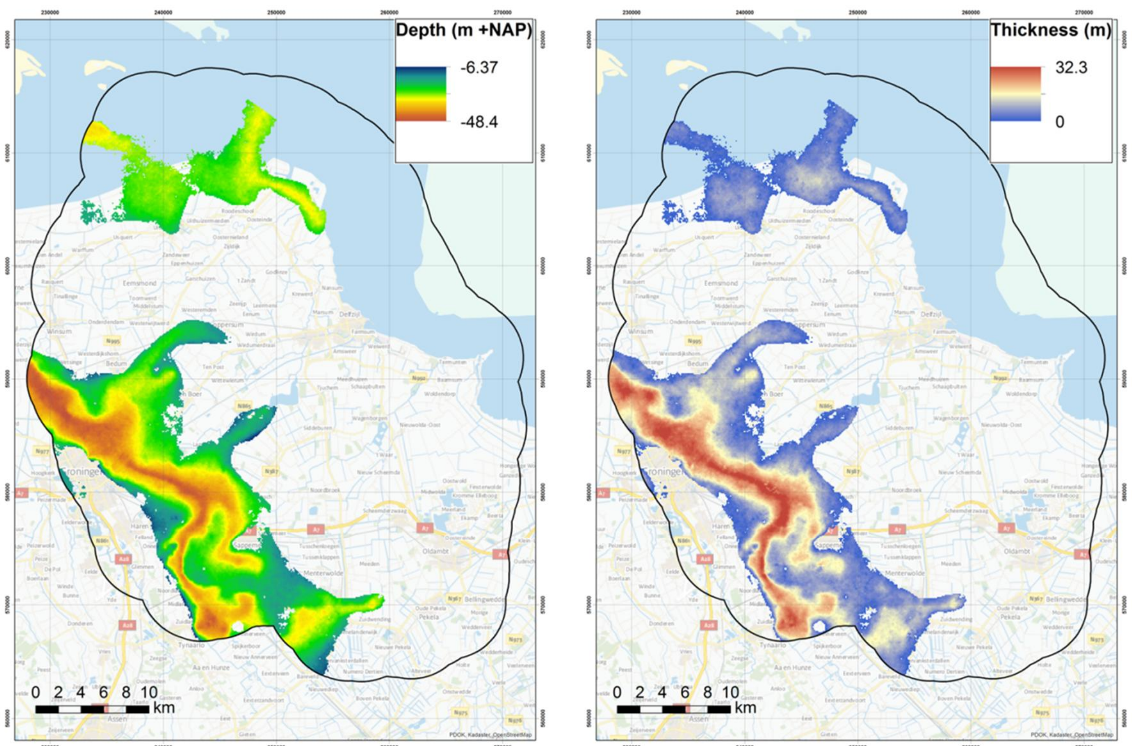

Figure 4.5 Depth of the base (left) and total thickness (right) of the Eem model unit in the GeoTOP 3D subsurface model (Maljers et al., 2016)

4.4 Drente Formation, Schaarsbergen Member

The Drente Formation consists of sediments that were formed by or near to the Saalian ice sheet (Saalian: 238 - 126 ka). In the research area, the Drente sediments are concentrated in the south in deep glacial valleys (Figure 4.6).

The fluvioglacial sediments consist mainly of medium coarse sands, but also fine and coarse sands are present. The sediments have been deposited in a fluvioglacial setting and were probably not exposed to ice-sheet loading. Therefore they are not assumed to be overconsolidated. Based on their high age, the sediments are expected to be less susceptible to liquefaction.

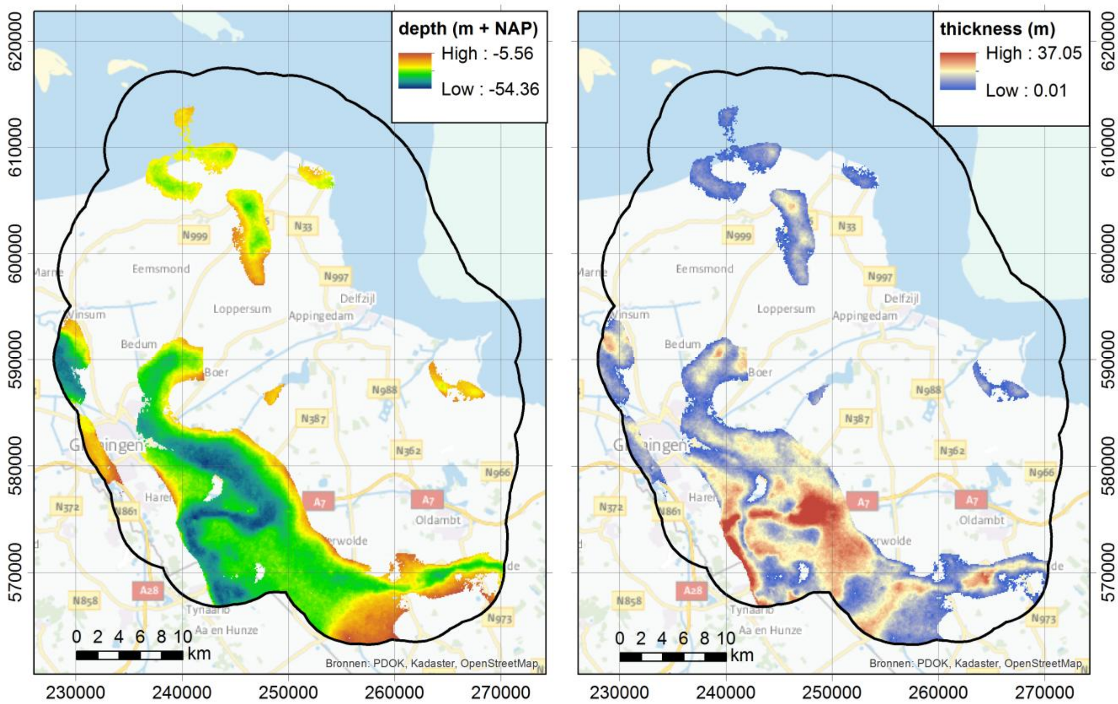

Figure 4.6 Depth of the base (left) and total thickness (right) of the Drente model unit in the GeoTOP 3D subsurface model (Maljers et al., 2016)

4.5 Urk Formation, Tynje Member

The Urk Formation, Tynje Member consists mostly of fluvial Rhine deposits and associated marine/estuarine deposits from Elsterian until Mid-Saalian age. The Member is only present in a small part in the north of the study area (Figure 4.7), and it can reach a thickness of around 15 m. The sandy deposits within this formation are subdivided into coarse channel deposits, channel deposits, levee and crevasse deposits, tidal channel and tidal flat deposits. Apart from these sandy deposits, the formation can consist of peaty marsh deposits and clayey or loamy lagoonal deposits.
The formation has experienced loading by an ice-sheet, and may be overconsolidated. Its high age makes it probably less susceptible to liquefaction.

The fluvial channel deposits consist mainly of clean non-calcareous sand ranging from very fine to extremely coarse, but also contains gravel beds. Some thin peat- or clay beds are present in this lithofacies. The sandy fluvial bank and crevasse deposits are very similar to

the fluvial channel deposits, but consist of thinner layers and more silty sand. The extremely coarse and gravel layers are lacking.
The marine tidal channel deposits are calcareous sand, ranging from medium fine to very coarse. The tidal flat facies consists mostly of clay, with some very fine to extremely fine sandy beds.

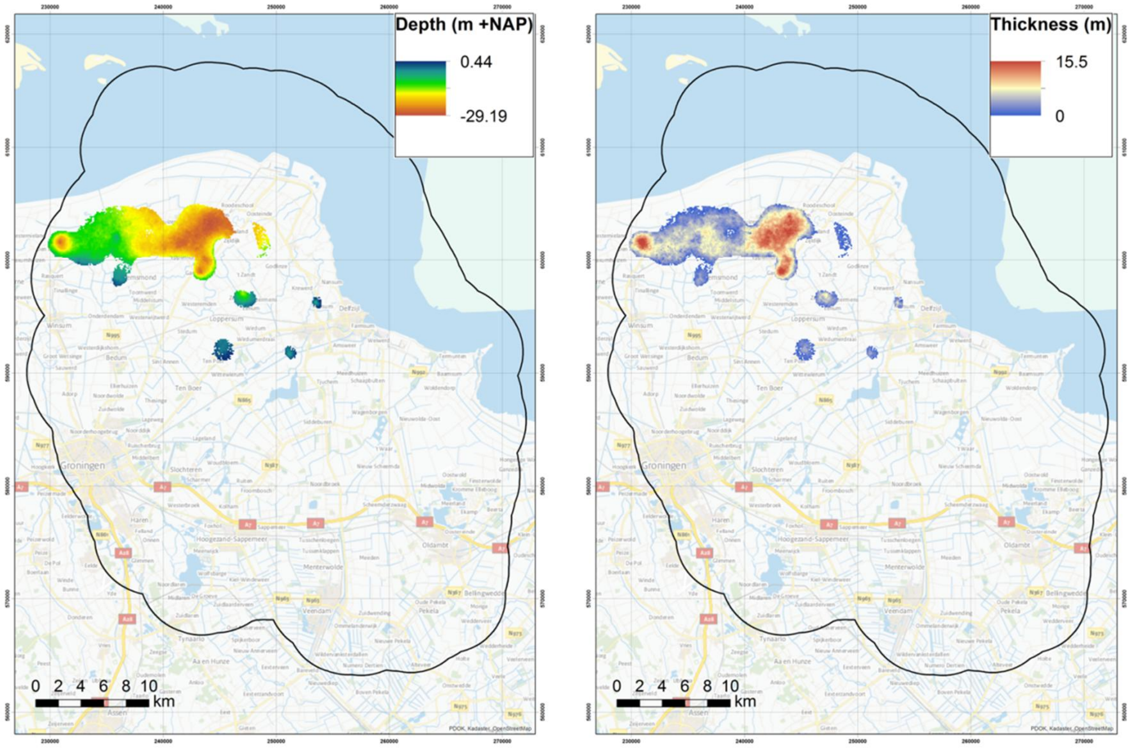

Figure 4.7 Depth of the base (left) and total thickness (right) of the Urk Formation, Tynje Member in the GeoTOP 3D subsurface model (Maljers et al., 2016)

4.6 Peelo Formation

The Peelo Formation is present in the entire research area (Figure 4.8). The sediments are interpreted to be related to glacial outbreaks, which explain the deep channel structures (“tunnel valleys”) of up to 240m deep in the area. The sands within the formation have been subdivided into a fine facies with sand median values generally below 210 µm and a coarse facies with generally higher values. In both cases, deposition has been attributed to melt water pulses in the Elsterian ice age (~475 – 410 ka). Apart from the sandy depositional facies, thick hard clay bodies are typical locally for the top of the formation. The sediments of the Peelo Formation have been exposed to ice-sheet loading, and may therefore be overconsolidated. In addition, the high age makes them less susceptible to liquefaction.

Characteristic of the Peelo Formation are its deeply incising valleys that can reach a depth of up to several hundreds of meters. They cut through the underlying sediments of the Veenhuizen Member (Urk Formation), Appelscha, Peize, Oosterhout and Breda Formations. The deep valleys lead to strong variation in depth over relatively short distances. These valleys are often interpreted as subglacial valleys that formed during melt water pulses. Directly after their formation, they have been filled with fluvioglacial sediments, during and after retreat of the ice front.

The sands range from very fine to extremely coarse, and are generally well sorted.

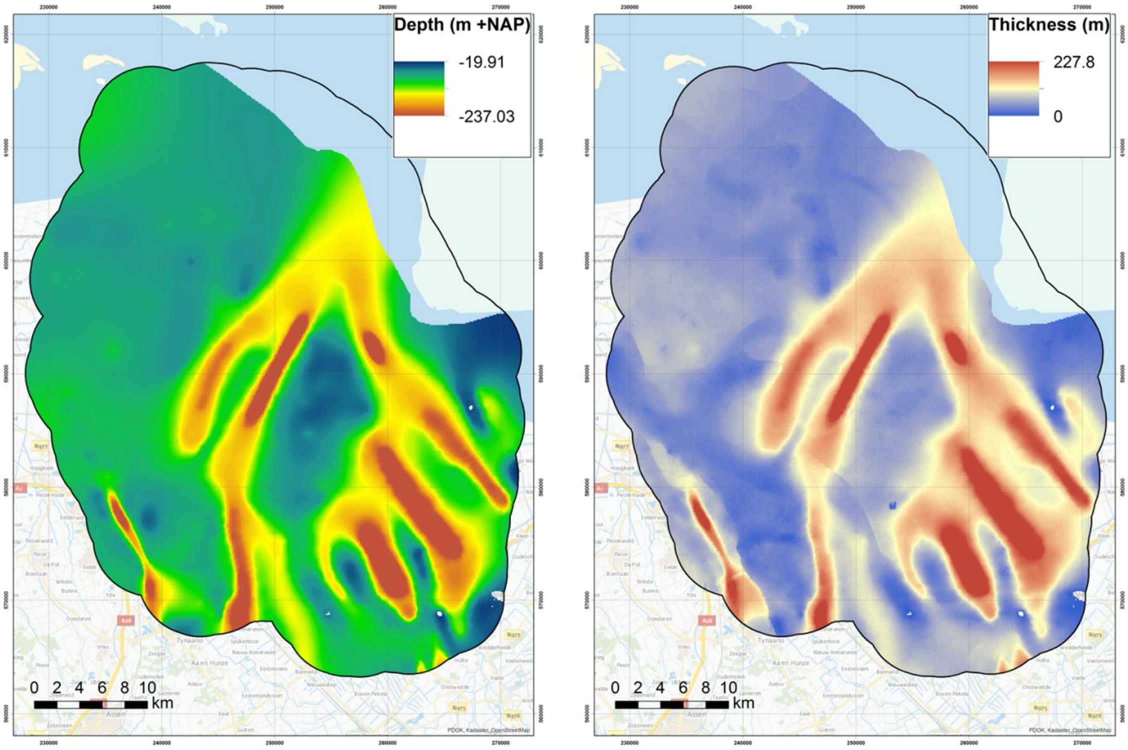

Figure 4.8 *Depth of the base (left) and total thickness (right) of the Peelo model unit in the GeoTOP 3D subsurface model (Maljers et al., 2016)*

5 Assessment method of liquefaction potential based on density

5.1 Introduction

The first assessment of the liquefaction potential for the Groningen field (+5 km buffer) is presented in this report. This chapter describes the method of analysing the CPTs and how they are related to the distinct geological areas. Since the subsurface is heterogeneous and the exact vertical subsurface profile at any specific location cannot be determined with certainty, a stochastic approach is preferred. In this study, the stochastic approach implies that for areas with a similar build up, a probability for the occurrence of dense, medium dense and loose sands is provided. In future, additions can be made for specific sand characteristics and/or liquefaction assessment methods from literature or specifically derived for Groningen.

5.2 Interpretation of the CPT data

In an ideal setting when detailed lithological log information is available for each CPT location, a statistical model could be constructed between CPT parameters (cone tip resistance (Qc) and Friction factor (Rf)) on the one hand and simplified lithologies from the boreholes on the other. There are many boreholes deeper than 20m in the study area (Figure 5.1). However, only few of these deep boreholes have reliable lithological information and a high resolution CPT nearby enough to represent the same subsurface sequence. A notable exception to this is the Top-Integraal borehole set (Bosch et al., 2014) which consists of high quality boreholes and corresponding CPTs nearby. Twelve of these borehole / CPT pairs are situated in the area. However, this set is not extensive enough to construct such a model. Therefore, existing statistical models have been used for now.

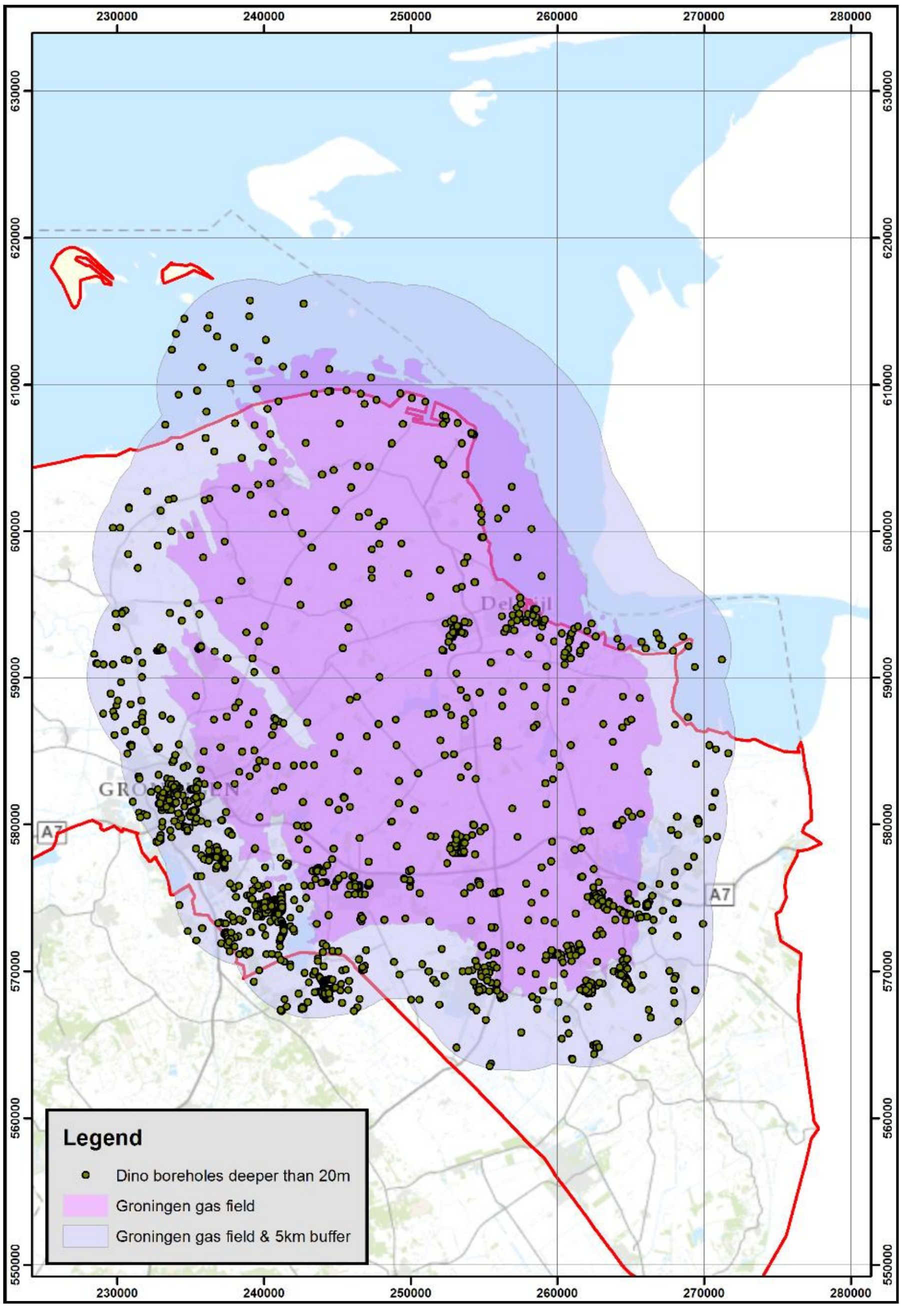

Figure 5.1 Locations of DINO boreholes with lithology logs and deeper than 20 m

A number of methods are available to convert CPT data (cone tip resistance (Qc) and Friction factor (Rf)) into an interpretation of simplified lithological units. In the literature graphs and charts from Robertson (1990), Douglas & Olson (1981) and Schmertmann (1978) can be found to arrive at an interpretation of lithology based on Qc and Rf values. The methods are often site-specific and different geological terrains and sediments in the subsoil will yield varying results. Experience learns that unconsolidated sediments as found in the project area will be interpreted most reliable. For this study the method of Douglas & Olson is used. Figure 5.2 shows their classification, based on Qc and Rf, as various lithological fields like sands, clays and peat and subdivisions in terms of grain sizes, mixtures and cohesive versus non-cohesive.

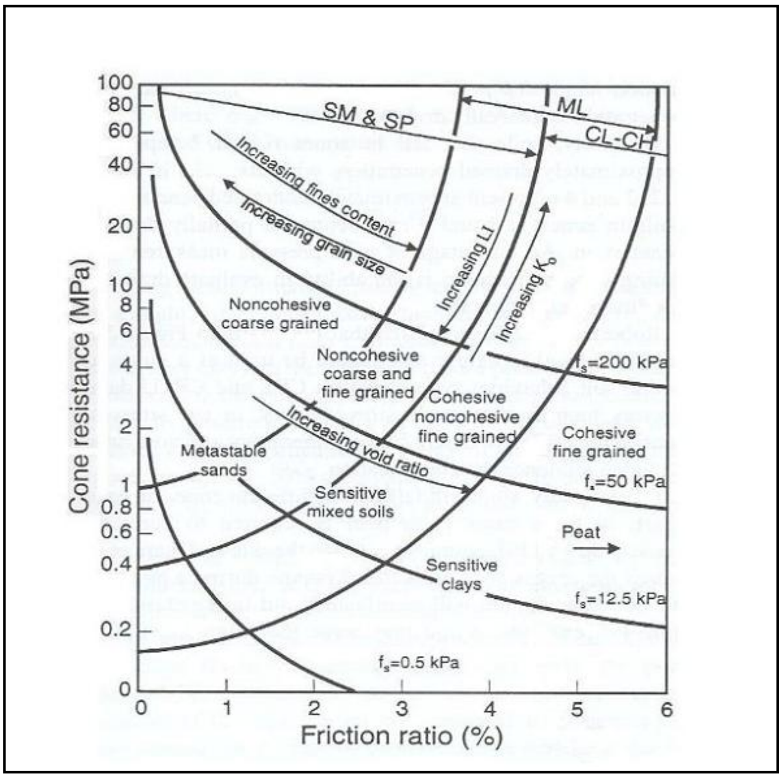

Figure 5.2 Original chart as proposed by Douglas & Olson to convert CPT data into simplified lithologies

Figure 5.3 shows a (Log) density map for all valid pairs of Qc and Rf for all CPTs, as shown in the map of Figure 3.1, and therefore represents all lithologies in the Holocene and Pleistocene units. The Douglas & Olsen line separating non-cohesive from cohesive sediments is adopted by conformal mapping and shown in Figure 5.3. The dividing lines between the four adopted lithologies have been modified to fit the density distribution and by correlation with nearby DINO / Top-Integraal boreholes with reliable lithology logs. The correlation here is based on the bulk of borehole information. This means that also less well described boreholes are included in the analysis. Nevertheless, the figure clearly shows the dominance of the sandy lithologies, in particular those belonging to the non-cohesive category. Note the pie diagram (inset), showing the distribution of derived lithologies, also indicating that the majority of Qc-Rf pairs can be classified as sands. Clayey and organic sediments are in the minority as they are found mainly in the top 5 meters of the Naaldwijk Formation.

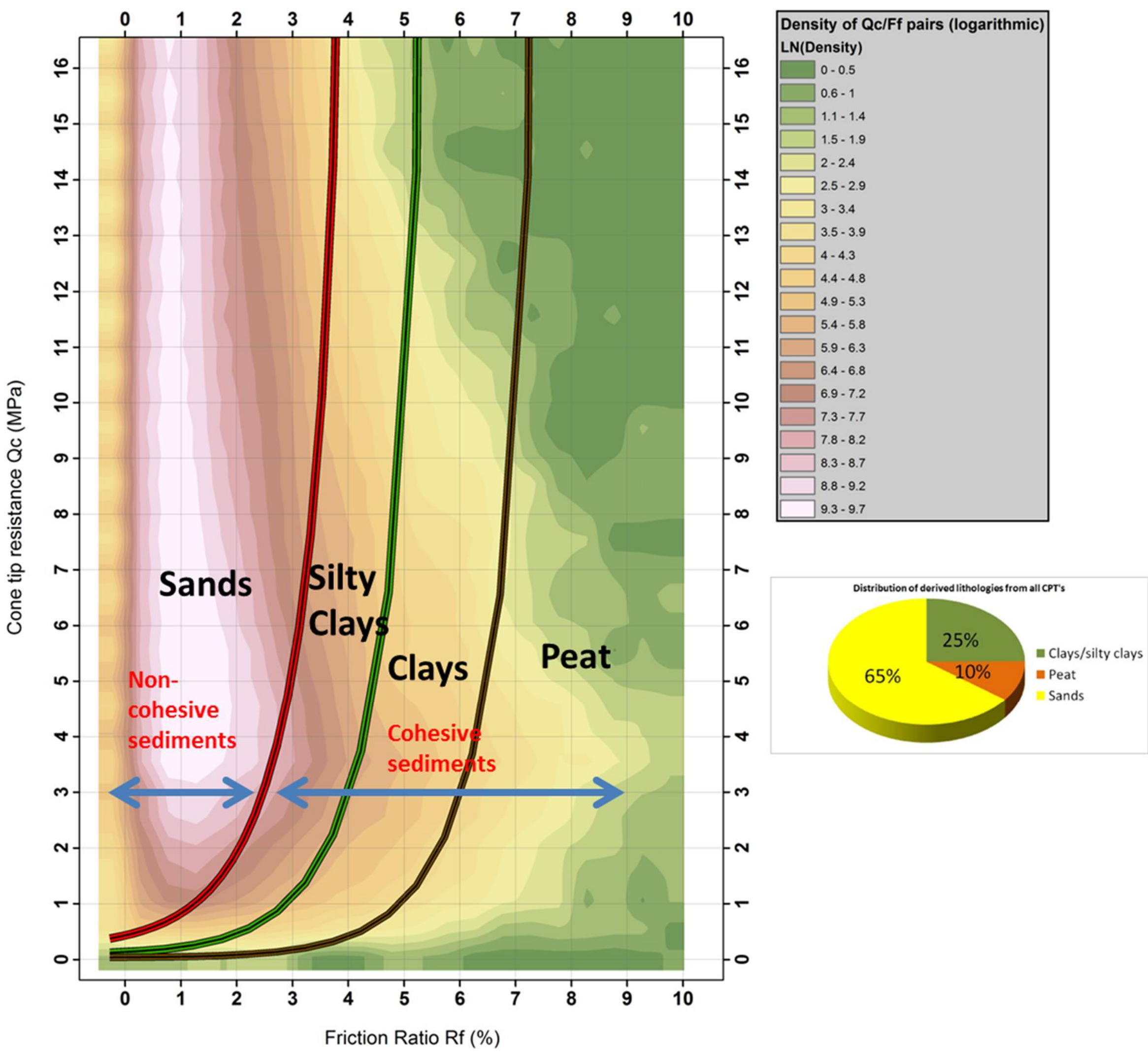

Figure 5.3 *Density (logarithmic) of all valid Qc-Rf pairs representing all lithologies in the CPT data set and dividing lines of the 4-Type lithology as adopted from Douglas & Olson charts and modified to fit the local conditions. The Pie diagram displays the distribution of derived lithologies, note the dominance of sandy lithologies*

The four types of lithologies as depicted in Figure 5.3, have been derived for all CPTs with valid Qc-Rf pairs. The results have been compiled into Rockworks™ version 16 projects. Figure 5.4 shows examples of the CPT data from two locations and the interpreted lithologies. Since this study is focussed on liquefaction, the next step is to determine the relative density of the sandy intervals.

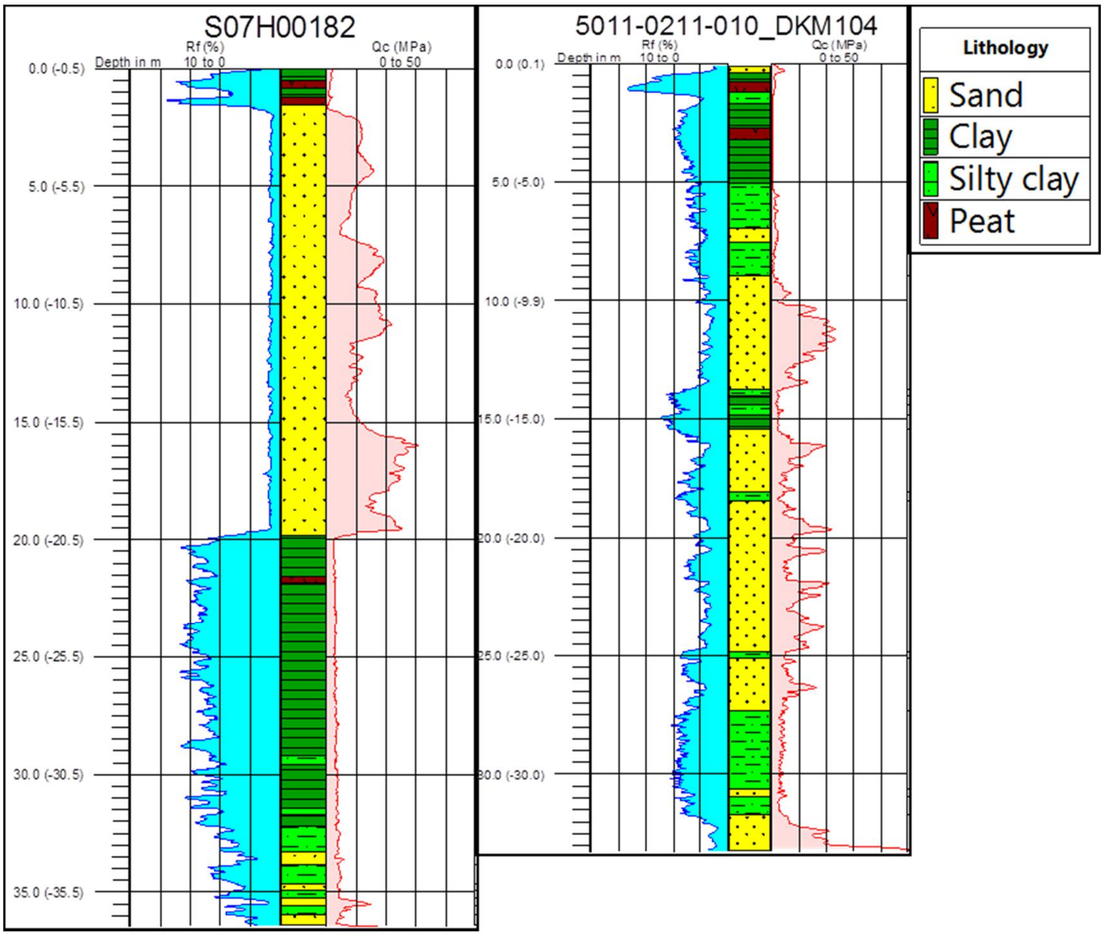

Figure 5.4 Example of a CPT from TNO-DINO (left) and Fugro (right) with the interpreted lithology according to the classification chart of Figure 5.3

5.3 Computation of relative sand layer densities from CPT data

5.3.1 Approach

After the process of deriving the lithologies from the CPT data, relative densities of the identified sand layers have been determined. The concept of “relative density” of noncohesive sediments and its validity is being debated in international forums. It is questioned whether two sediment types with similar relative densities may also exhibit similar geotechnical properties. Relative density is influenced by grain shape, sorting, cementation, stratification, etc. The same applies to the estimation of relative density from CPT data, in particular from the cone tip resistance. A variety of computational methods can be found in the literature giving the impression of a site-specific parameter. Nevertheless, it is attempted to derive the relative densities of sand layers by common methods and to compile maps showing the distribution of loose, medium dense and dense sands over the project area. Based on Deltares experience with the calculation of relative density of sand for the Groene Hart tunnel in The Netherlands, the methods of Lunne & Christofferson (1983) and Villet & Mitchell (1981) proved to yield the most reliable results. It is obvious that the geological setting in Groningen partially differs from the setting at the Groene Hart Tunnel, but these results are assumed to be applicable to the Groningen study as well for the moment. Especially during the Holocene both areas have experienced a similar evolution, resulting in similar types of deposits.

These two computational methods have been applied to the CPT data:

$$Dr = \frac{1}{2.91} * \ln\left[\frac{Qc * 1000}{61 * (\sigma)^{0.71}}\right] * 100\%$$

for Lunne & Christofferson (1983) and the other one by Villet & Mitchell (1981):

$$Dr = \frac{[Qc + 0.0000088 * \sigma^2 - 0.0055 * \sigma]}{[0.205 * \sigma - 0.0001969 * \sigma^2]} * 100\%$$

Where:
Dr is the relative density in percentages
Qc is the cone tip resistance in MPa
σ is the effective stress in kPa

5.3.2 Thin layer correction or transition zones between sand and clay

At the transition from clay to sand or sand to clay a transition zone is present where in the sand layer the measured cone resistance is decreased by the clay layer. Using the measured cone resistance in this transition zone will underestimate the density and thus overestimate the risk of liquefaction. This effect is comparable to the 'thin layer correction' in the literature. Only a limited number of investigations are known on the thickness of this transition zone and the reduction in cone resistance in this transition zone. If the soft soil layer is relatively thin (< 0.4 m), the entire layer is a transition zone. These include Idriss and Boulanger (2008), see Figure 5.5.

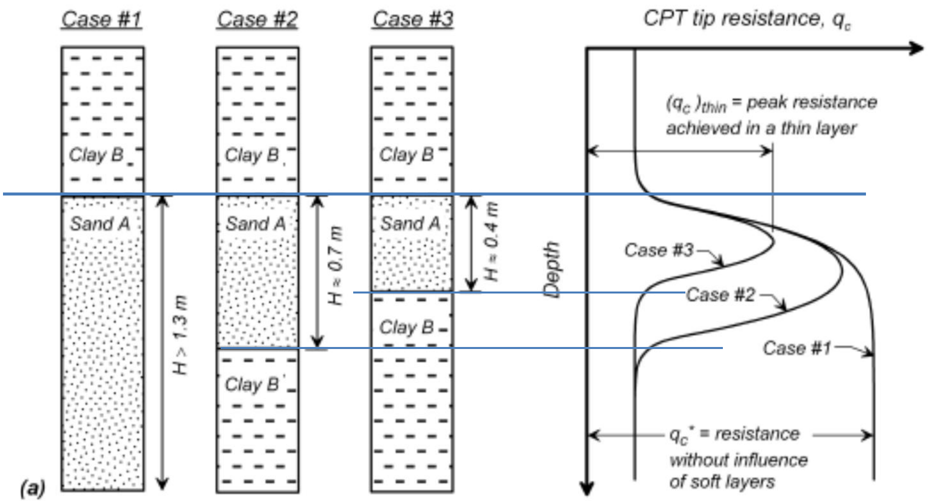

Figure 5.5 Illustration effect thin soft layers on measured cone resistance in sand layer. Figure taken from Idriss and Boulanger (2008)

Ahmadi and Robertson (2005) give results of FLAC calculations for the measured cone resistance at a transition zone. They found that the thickness of the transition zone increases when the difference in the cone resistance of the two layers increases. The thickness of the transition zone in their example is about 0.25 m. In the calculations the dimensions a standard cone (diameter 0.036m) were used. Van den Berg (1994) found for the situation of clay on sand that the thickness of the transition zone is about 0.1 m, which is around 3 times the cone diameter d_c.

The thin layer correction from Youd et al (2001), recommended in Idriss and Boulanger (2008) suggests the correction of the cone resistance in thin layers depends on the layer thickness, see Figure 5.6.

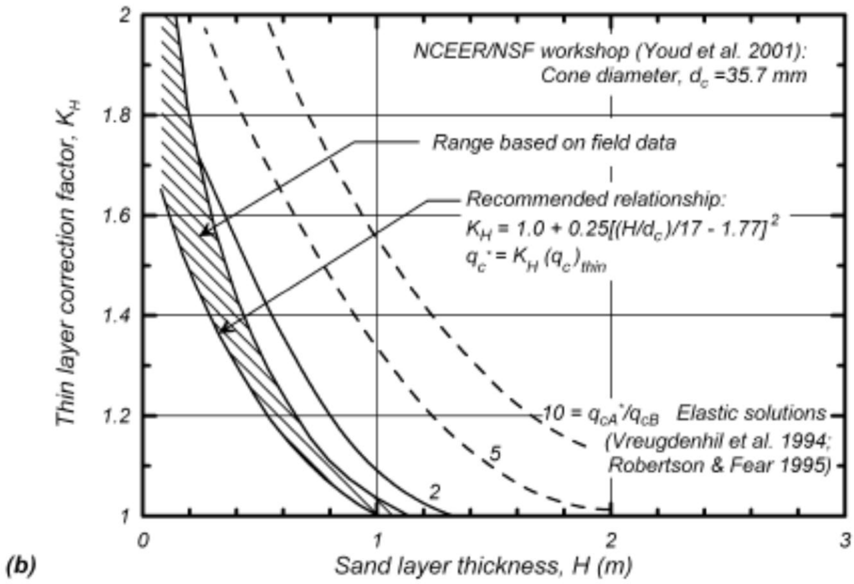

Figure 5.6 Thin layer correction KH for determining equivalent thick-layer CPT tip resistance, relationship recommended in Youd et al (2001), figure taken from Idriss and Boulanger (2008)

For the GLG model, a similar type of correction factor was derived by comparing the average CPT values within the ‘unaffected’ part of the sand layer, with the CPT values along a zone of 20 cm in the top and 20 cm at the bottom of a sand layer. Statistical analysis of the recorded Qc values in the top and bottom zones as compared to the Qc mean values in the sand layer indicated that a factor of about 2.5 exists between these zones. Since both the bottom and the top zones are used, there is no bias in these values for depth or thickness of the layer. This factor is applied to correct the underestimated Qc values in these top and bottom zones. Since the factor that was found is higher than the factor found from literature (lower estimates around 1.5) we compared the results of the densities with correction factor of 1.5 and 2.5 and found very small differences (5% in average relative density over all the sand layers).

After applying this methodology on all valid CPTs a total of about 2.9 million values for relative density were calculated by both the Lunne & Christofferson and the Villet & Mitchell method. The results show that *Dr* values calculated by Lunne & Christofferson are slightly higher than the ones calculated by Villet & Mitchell.

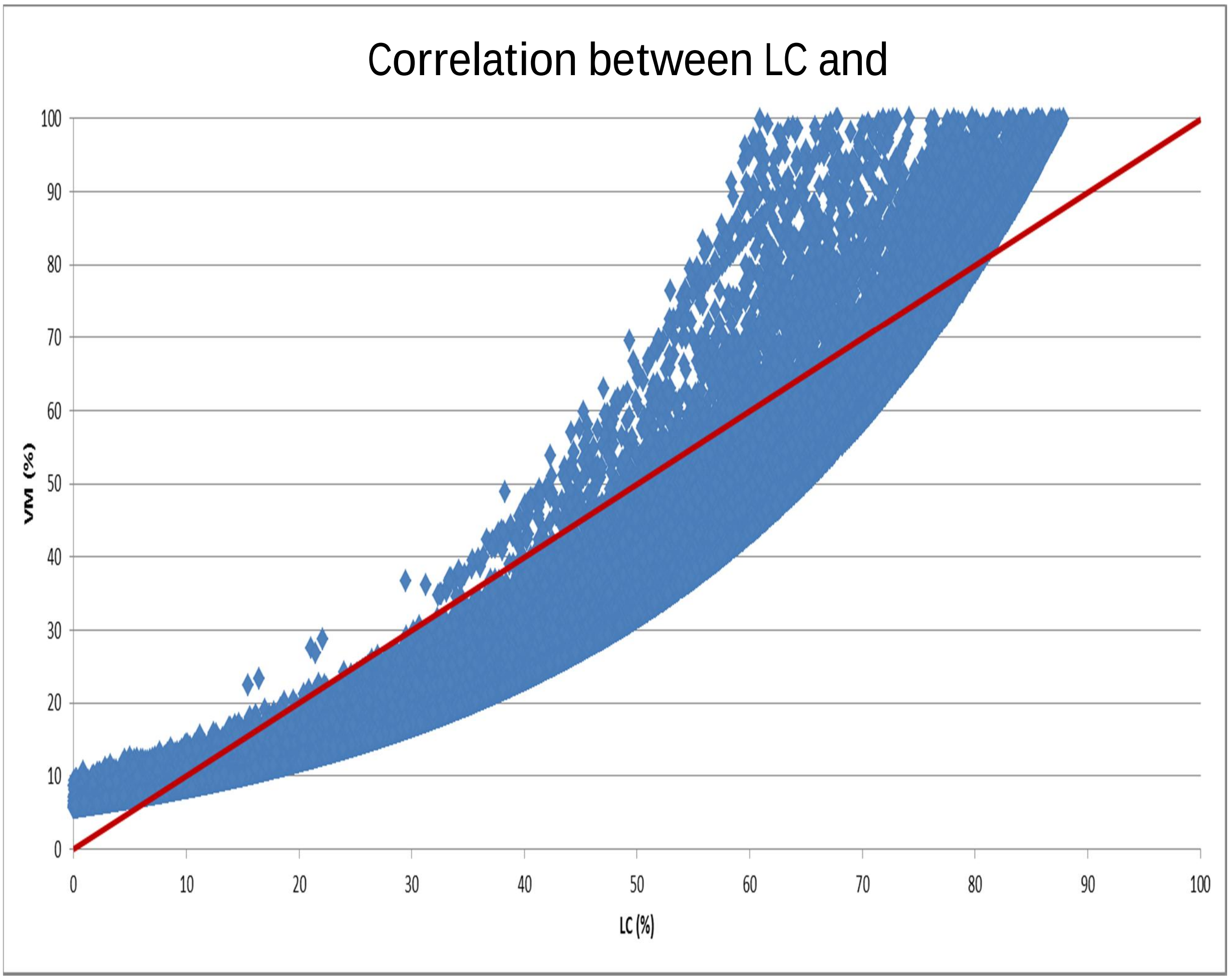

Figure 5.7 Correlation between the calculated relative densities by the methods of Lunne & Christofferson (LC) and Villet & Mitchell (VM) and the 1:1 line in red

The relationship between the two calculated parameters for relative density is depicted in Figure 5.7. For values below ca. 10% and above ca. 75% of the relative density calculated with the Lunne & Christofferson (LC) the corresponding value calculated with Villet & Mitchell (VM) is higher, whereas this relationship is reversed between these values. At the same time the noisiness increases, based on the plotted points. Nevertheless, an exponential fitting curve can be established between the two parameters.

The classification of loose, medium dense and dense sands follows the generally agreed values in the literature of <35% indicating loose sands, medium dense sands between 35% and 65% and dense sands > 65%. From this it follows that for values less than 65%, thus for loose and medium dense sands, the Lunne & Christofferson parameter is more conservative. In all the resulting maps, the method of Lunne and Christofferson is used, leading to slightly conservative values.

5.4 Calculation of sand densities for model units

The computation in the previous step results in a classification of the CPT values in loose, medium dense and dense sands over the entire depth range. To give a meaningful estimation of the sensitivity to liquefaction over larger areas, the sand density classes must be grouped

into meaningful units. It can be expected that the properties of the sand are related to depositional environment and age. Both are included in the classification of geological units, and hence it makes sense to group CPT values according to geological units.
The shallow subsurface in Groningen is relatively well mapped and digitally represented by the GeoTOP model. Based on the official version of GeoTop Oostwadden v1.0, at least six geological units can be distinguished which are being penetrated, partly or fully, by the majority of the CPTs in the project area. These units have been introduced in Chapter 4 and in chronological (young to old) order are:

Holocene age:
- Naaldwijk unit (Marine tidal flat deposits).

Pleistocene age:
- Boxtel unit (periglacial aeolian and local fluvial deposits).
- Eem unit (Marine tidal flat deposits).
- Drente unit, Schaarsbergen Member (Fluvioglacial deposits).
- Urk unit, Tynje Member (Fluvial and marine tidal deposits).
- Peelo unit (Glacial outwash deposits).

Part of the GeoTOP Oostwadden dataset consists of the geometries of the model units, defining the depth of the top and the base in the form of GIS grid layers. For every CPT, the sand density classes were grouped by GeoTOP model unit by dividing the CPT record using the depth of the base and the top of the relevant model units at that location.

Not many CPTs penetrated the deeper Pleistocene model units. Within these units loose sands were a minority. Therefore, it was decided to start with an analysis of the sand density distribution separated in Holocene and Pleistocene model units. Since the thickness of the Holocene Naaldwijk model unit varies a lot over the area of interest, the model unit was analysed for the sand density in depth ranges of 5 m. Subsequently, the Pleistocene units were analysed separately for the range between 0 and 20m, and between 20 and 40m below surface level.

6 Distribution of relative sand densities

6.1 Available CPT data sets used to derive the sand densities

For this analysis, a selection of CPTs was made: only CPTs with continuous data of cone tip resistance and sleeve friction were used, and the record had to be longer than 5m. This led to a selection of 4285 CPTs (Figure 6.1, Figure 6.2). From these selected CPTs, maps have been compiled showing the CPT locations and the accumulated thickness of loose, medium dense and dense sands within the Naaldwijk model unit and the Pleistocene units.

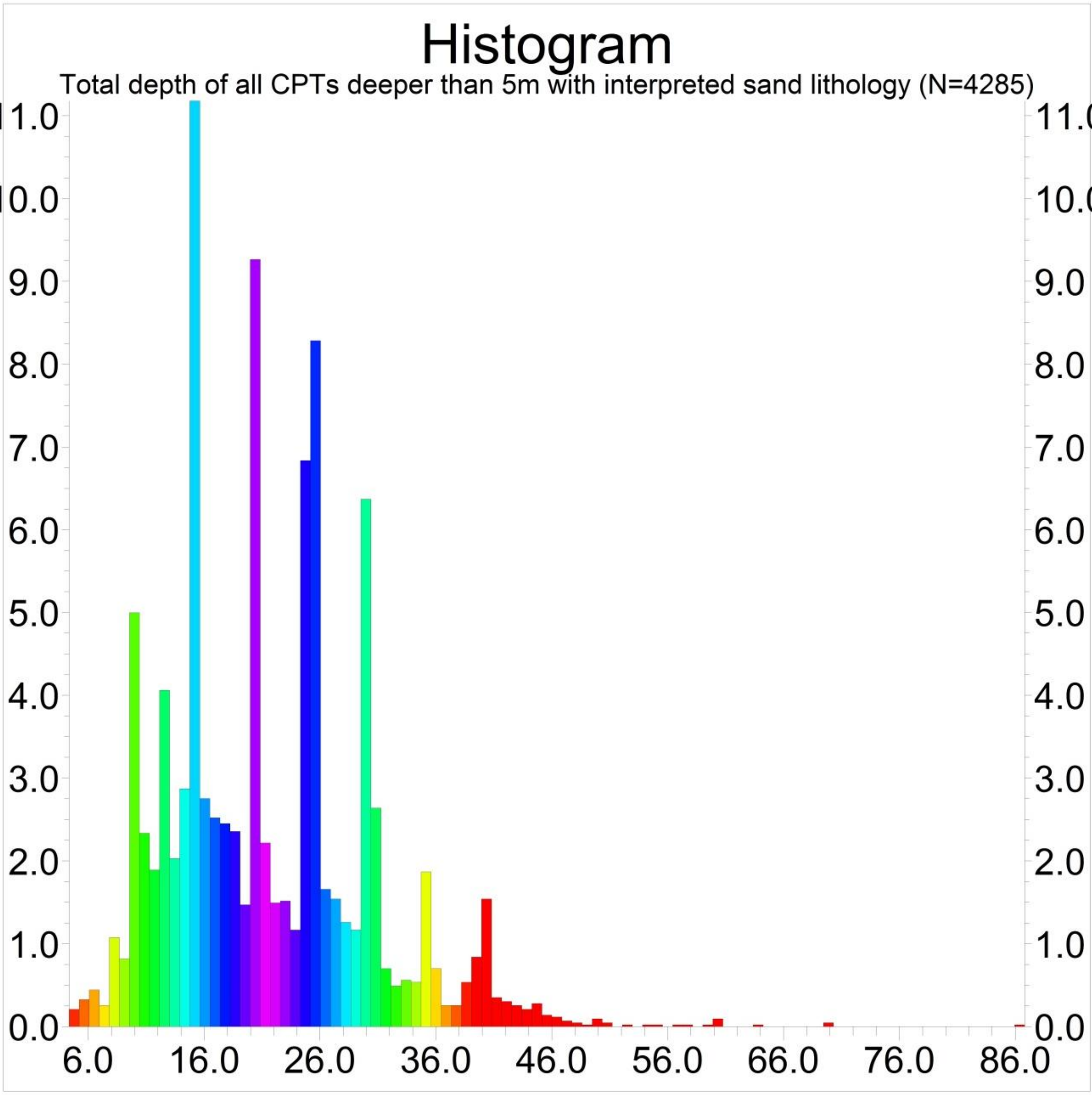

Figure 6.1 Histogram of the total depth distribution of CPTs penetrating sandy layers from which the relative densities have been calculated

The histogram in Figure 6.1 shows that the total depth distribution is symmetrical with a mean around 20m NAP and that the number of CPTs reaching depths of at least 30 m NAP reduces considerably.

The analysis was separately performed for the Holocene Naaldwijk unit and the Pleistocene model units. For the Pleistocene units, the analysis was carried out for the depth zones of 0 to 20 m minus surface level and the zone between 20 and 40 m minus surface level to determine the effect of depth. Since the Naaldwijk unit only locally reaches over 20 m of depth without exceeding 25m below surface in the study area, this formation is considered as a single unit.
CPTs were only used if they are deeper than 5 m and penetrate at least 75% of the thickness of the unit. For the analysis between 20 m and 40m below the surface, only CPTs deeper that 35 m were used. For the analysis of relative sand densities between 0 - 5 m, 5 - 10 m, 10-15 m and 15-20m, all CPTs penetrating those depths were used. Per figure the selection criteria for the CPTs has been given. Figure 6.2 shows all the CPTs from which relative densities have been derived using the methodology as described in Paragraph 5.4.

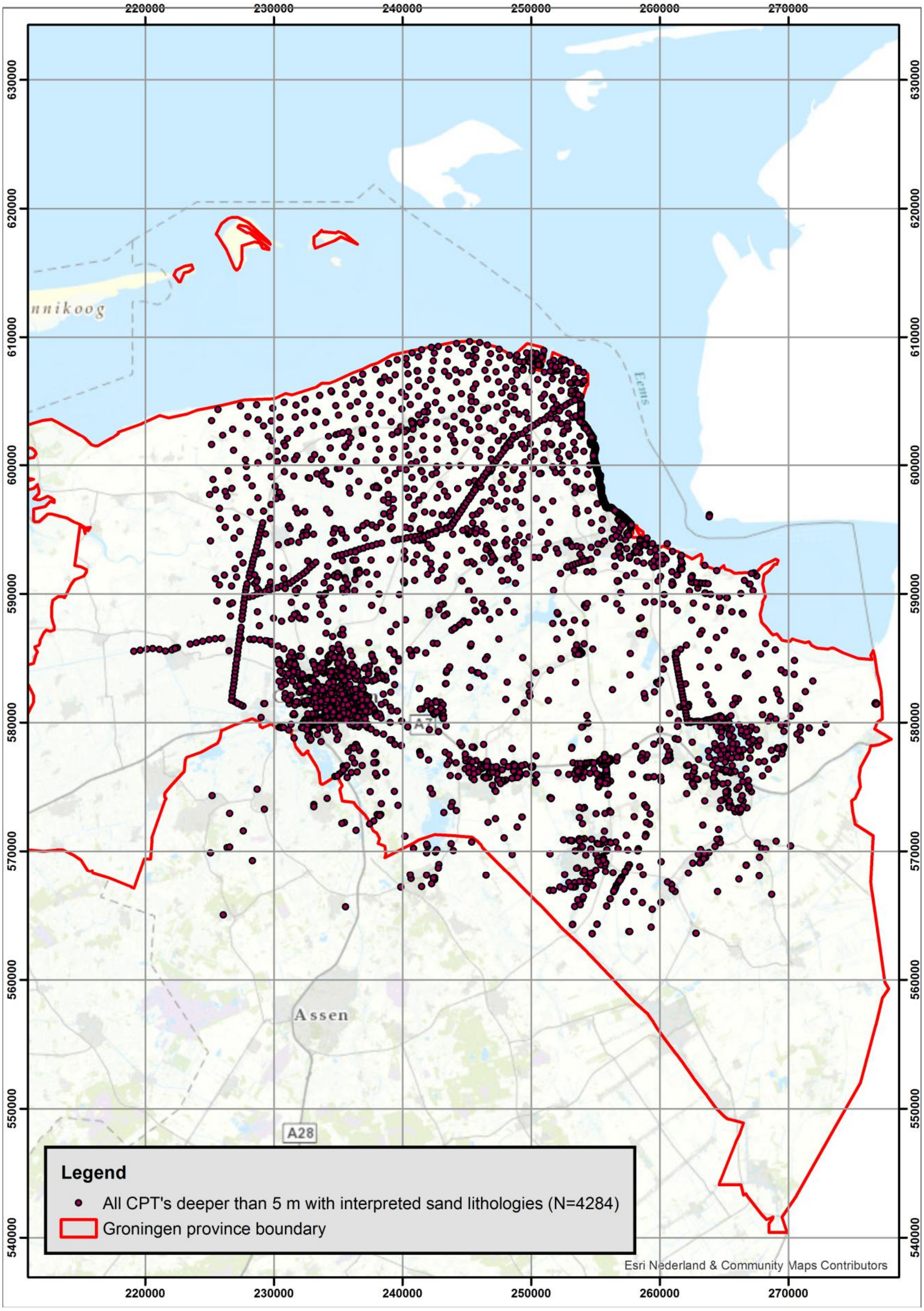

Figure 6.2 All CPT locations with sandy layers used in the derivation of relative sand densities (n=4284)

6.2 Relative sand density distribution in the Naaldwijk unit in the top 20 m below the surface

The histograms of the accumulated thicknesses of loose, medium dense and dense sands show (Figure 6.3, Figure 6.4 and Figure 6.5) that most of the intervals are thin. The thickness of the accumulated sand intervals of a certain density in the Naaldwijk unit is mostly less than 1.5 meters. In the North of Groningen, close to the Waddenzee, the sands become dominant and much thicker deposits consist of mainly loose sands (Figure 6.6). The accumulated thicknesses may reach up to over 10 metres. This area corresponds with the location of sandy tidal channel deposits of the Naaldwijk unit. Considering the sandy CPTs, 705 CPTs do not contain loose sands. These are all CPTs with very low accumulated sand thickness (Figure 6.7).

Interesting is the occurrence of thicker accumulations of loose, medium dense and dense sands in the areas near Groningen city and extending in NW direction (Figure 6.6 and Figure 6.7). This can most likely be attributed to the Holocene marine invasion of the Hunze valley and the infill with sandy deposits in a tidal setting.

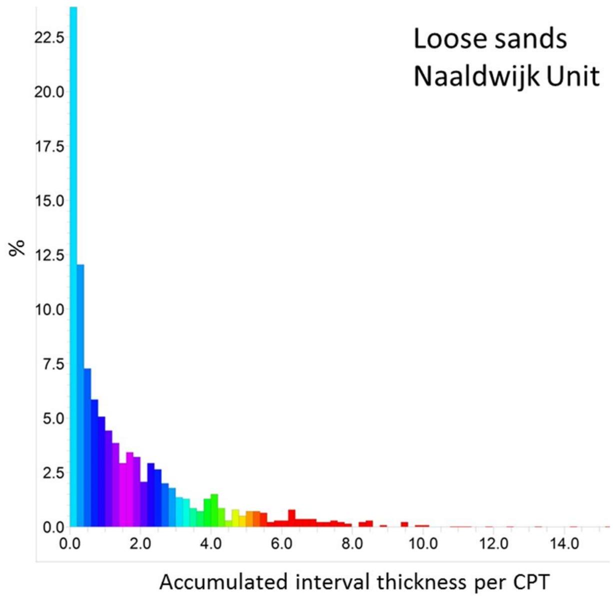

Figure 6.3 Histogram of the accumulated thicknesses of loose sands in the Naaldwijk Unit

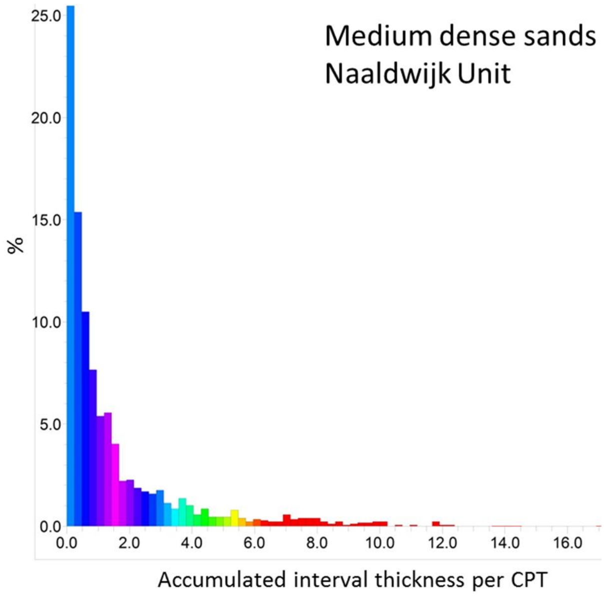

Figure 6.4 Histogram of the accumulated thicknesses of medium dense sands in the Naaldwijk Unit

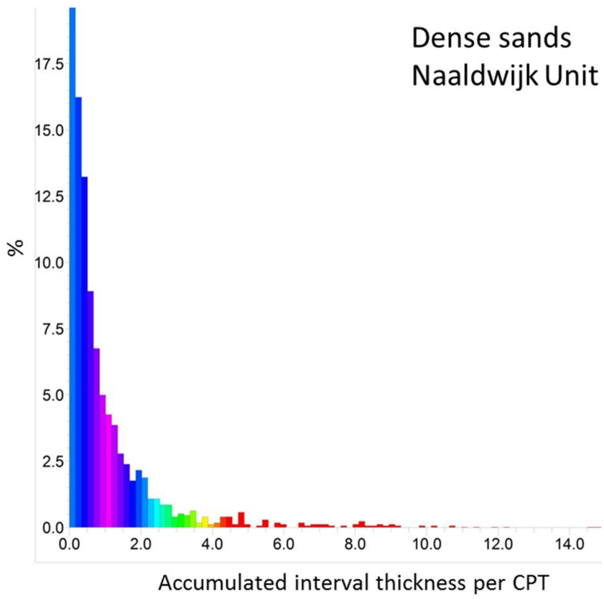

Figure 6.5 Histogram of the accumulated thicknesses of dense sands in the Naaldwijk Unit

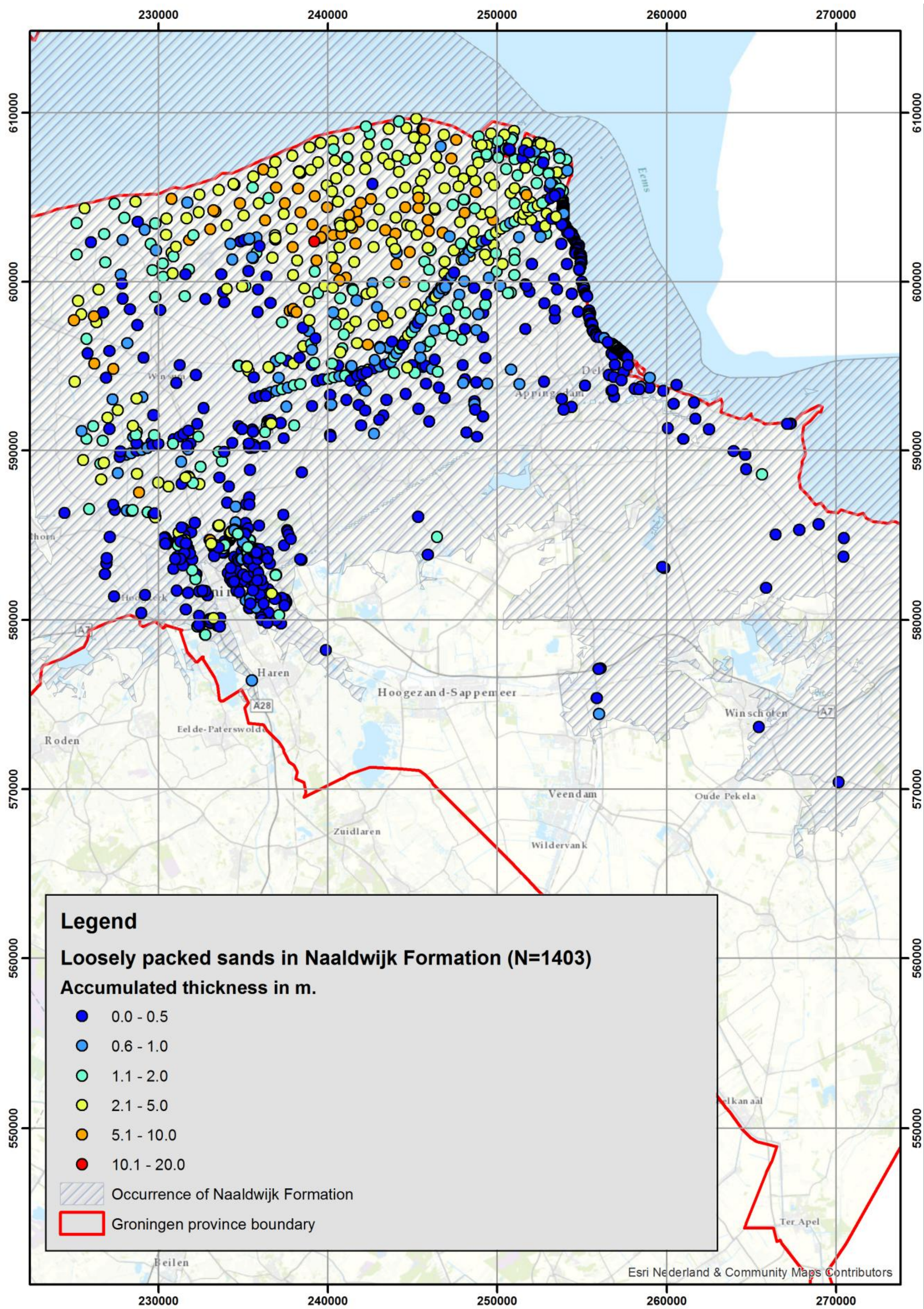

Figure 6.6 Accumulated thicknesses of loose sands estimated from CPTs (n=1403) penetrating at least 75% of the Naaldwijk unit

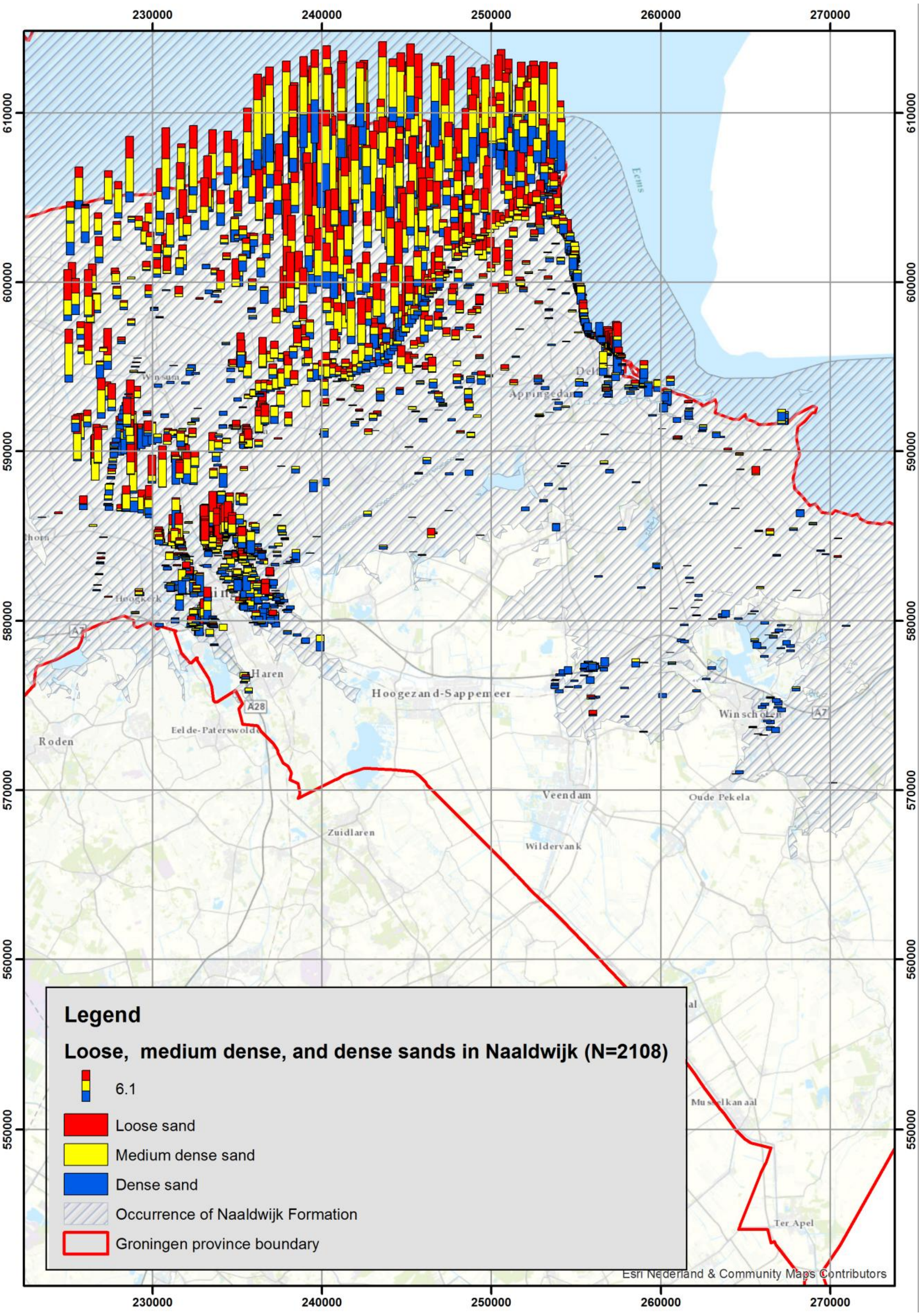

Figure 6.7 Distribution of loose, medium dense and dense sand in CPts in the Naaldwijk unit

6.3 Relative sand density distribution in the Pleistocene sediments in the top 20 m below surface

The Pleistocene units Boxtel, Eem and Drente, Urk and Peelo are mainly composed of sand. The thickness of the total Pleistocene sediment pile in Groningen reaches between 100 m and 220m.

For the top 20 m below the surface, of these Pleistocene deposits, the histograms of the accumulated thicknesses of loose, medium dense and dense sands (Figure 6.8, Figure 6.9 and Figure 6.10) show that the accumulated loose sands per CPT are mostly thin. This contrasts with the accumulated thicknesses of medium dense and dense sands which consist generally of much thicker intervals.

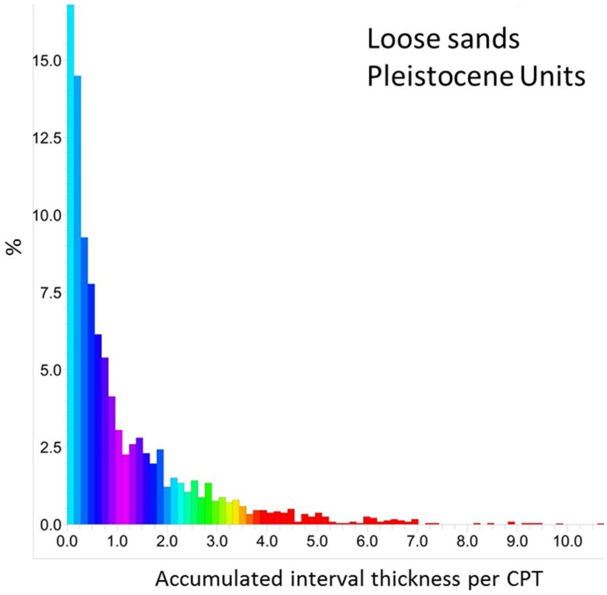

Figure 6.8 Histogram of the accumulated thicknesses of loose sands in the upper 20 m of the Pleistocene

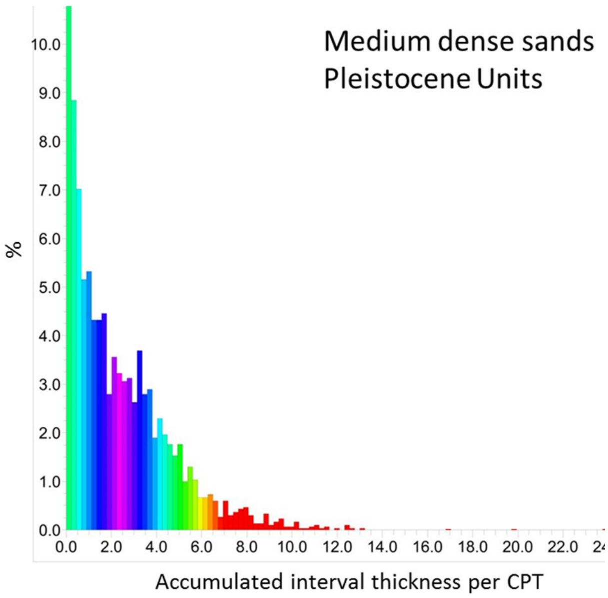

Figure 6.9 Histogram of the accumulated thicknesses of medium dense sands in the upper 20 m of the Pleistocene

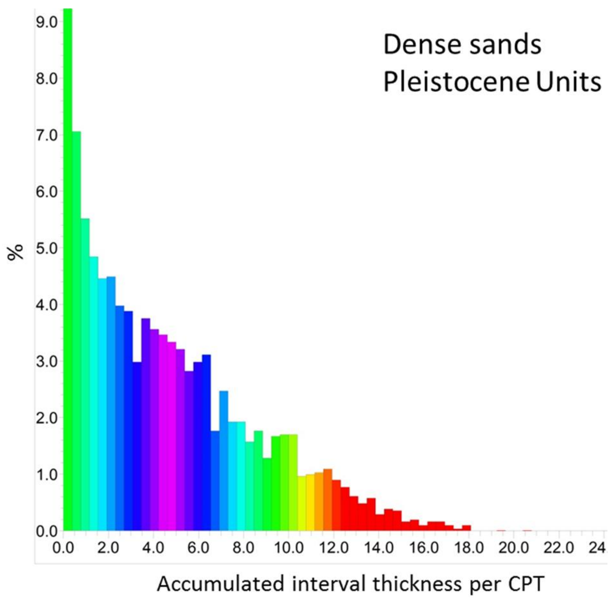

Figure 6.10 Histogram of the accumulated thicknesses of dense sands in the upper 20 m of the Pleistocene

This fits well with the overall sandy nature of these Pleistocene deposits. It also suggests that the Pleistocene deposits contain relatively more medium dense and dense sand.

The distribution of loose sands in the Pleistocene units to 20 m below the surface in the project area is shown in Figure 6.11. The thickness variation over the area matches the histogram of Figure 6.8. The majority of accumulated thickness does not surpass ca. 1.5 m. Some higher thicknesses are to be found near the city of Groningen and in the north which are most probably linked to the patchy occurrence of the sandy tidal channel deposits of the marine interglacial Eem unit. The distribution of loose sands in the top of the Pleistocene contrasts with the much thicker accumulations of loose sands in the overlying Naaldwijk unit. Of the sandy CPTs in the Pleistocene units, 883 CPTs do not contain loose sands. These are all CPTs with very low accumulated sand thicknesses (Figure 6.12).

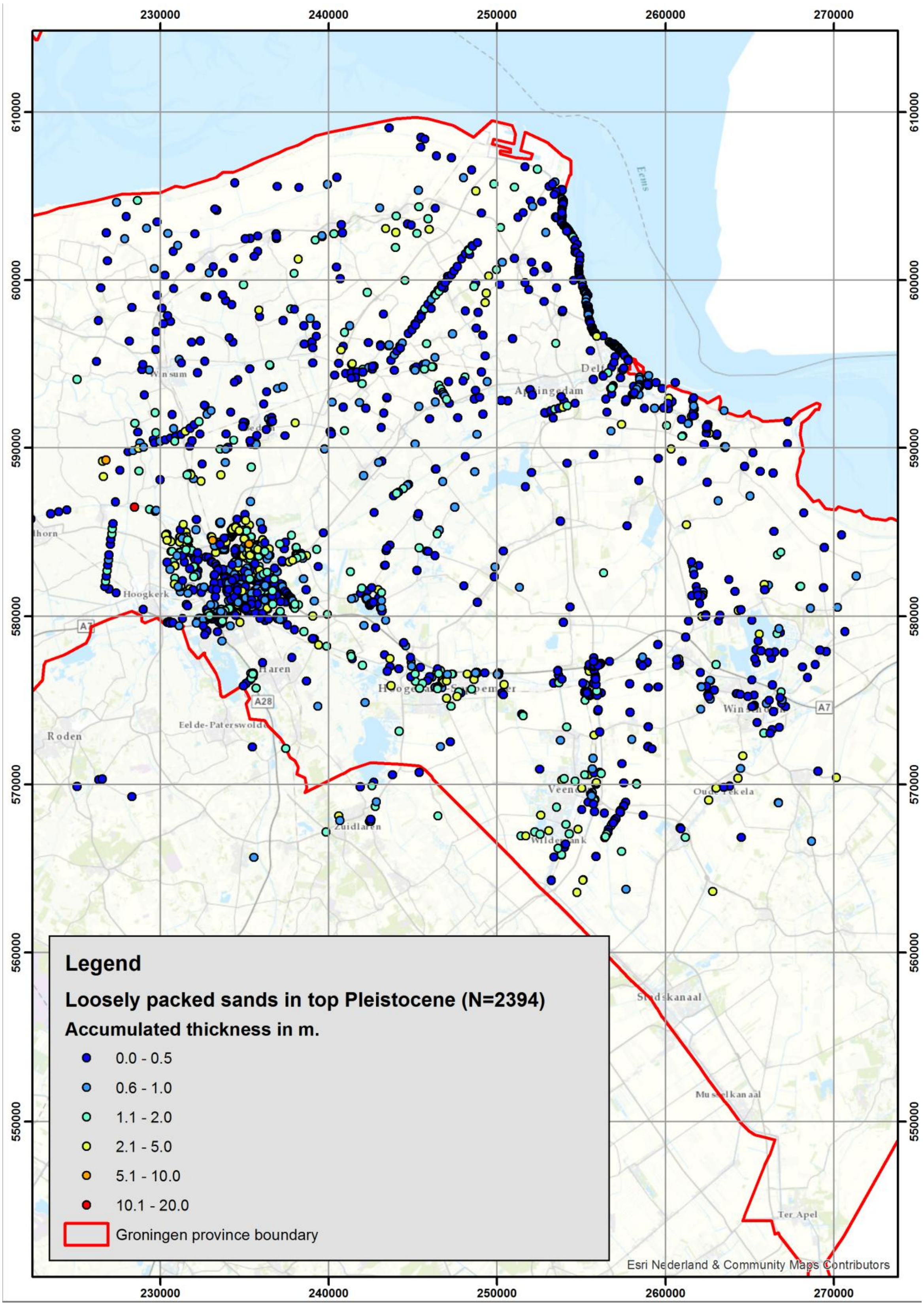

Figure 6.11 Accumulated thicknesses of loose sands in Pleistocene model units up to 20m below the surface (n=2394)

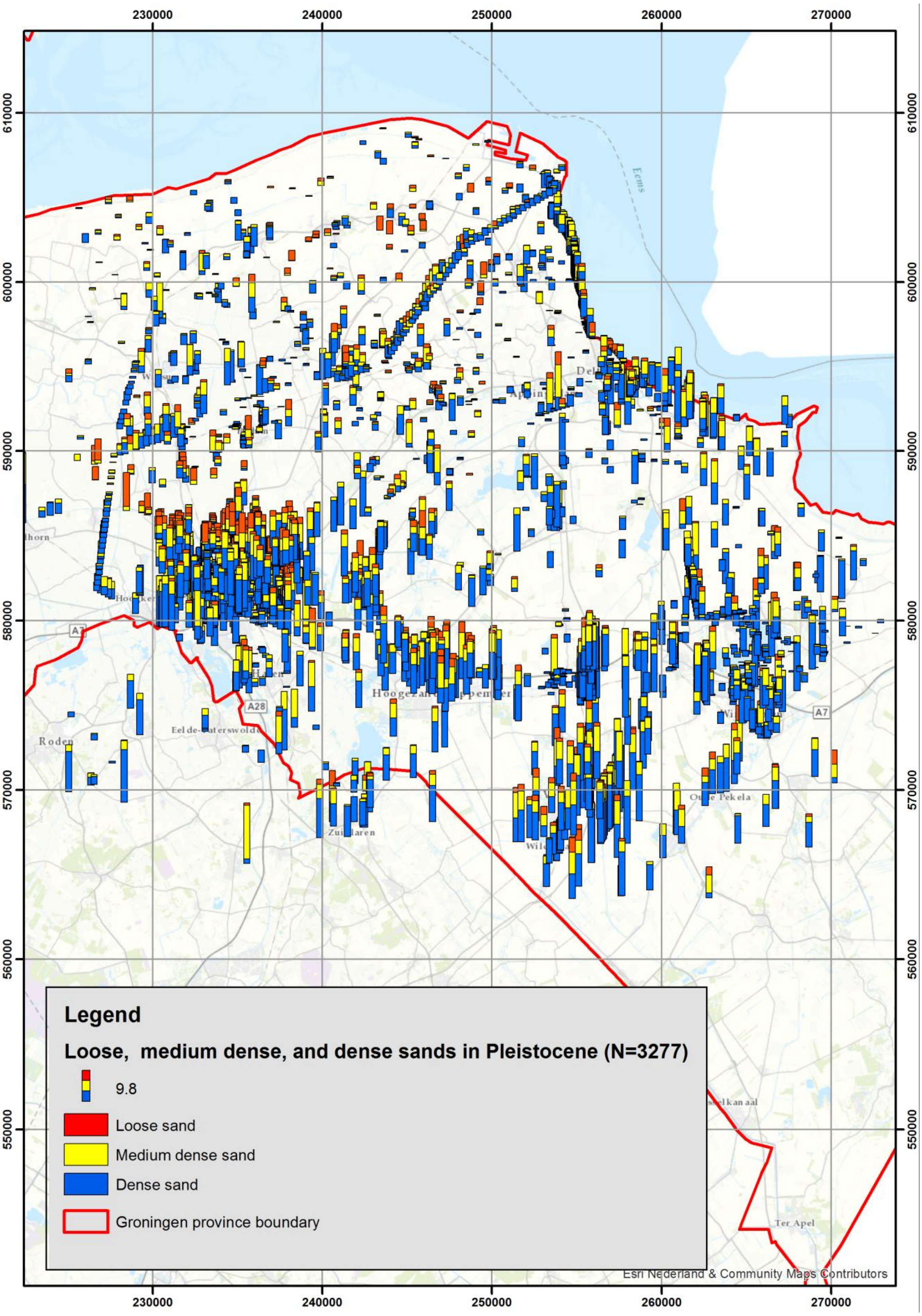

Figure 6.12 Distribution of loose, medium dense and dense sand in CPTs in the Pleistocene units from 0 to 20m below surface. A thickness scale (9.8) is given in the legend, expressed in m.

6.4 Relative sand density distribution in Pleistocene sediments between 20 m and 40 m below the surface

The number of CPTs that penetrate deeper than 20 m into the subsurface decreases rapidly with increasing depth. A total of 558 CPTs penetrate the depth range from 20 to 40m for 75% or more. Also in this depth range, loose sand can be found (Figure 6.13). Especially in the north and around the city of Groningen, loose sands with an accumulated thickness of several meters are present. This is the area covered by the Naaldwijk model unit. Possibly, the depth of the Naaldwijk model unit is underestimated and the loose sands actually belong to this Holocene unit. On the other hand, also Pleistocene units may contain significant amounts of loose sands. This applies mainly to the Eem Formation consisting of similar types of interglacial deposits.

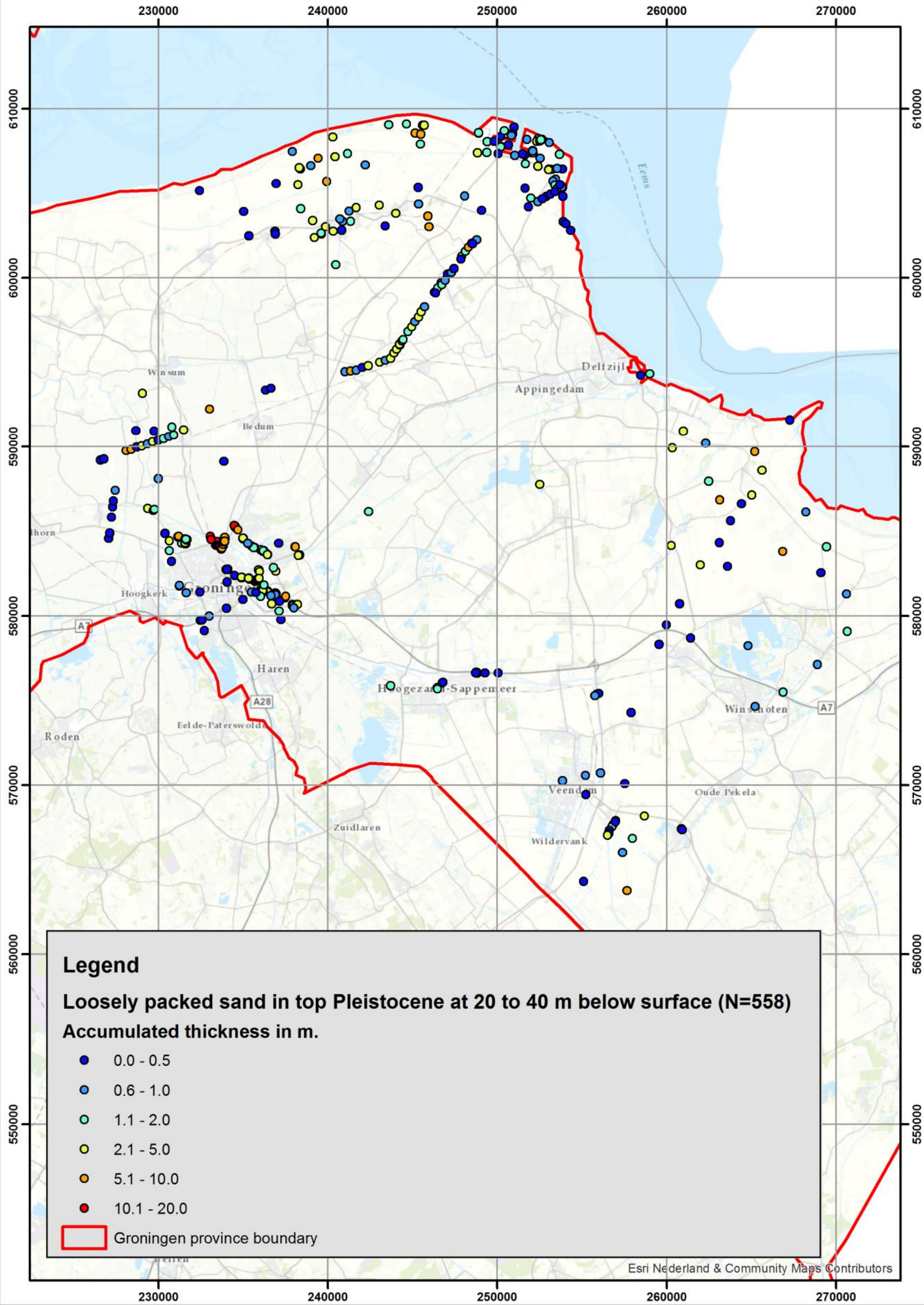

Figure 6.13 Accumulated thickness of loosely packed sand in Pleistocene units between 20 and 40m below the surface

6.5 Relative sand density distribution in subareas of the Naaldwijk unit

As this study focusses on the occurrence of loose sands and their lateral and vertical distribution, it stands to reason to investigate the distribution within the geological units. In the previous chapters it is shown that the loose sands widely occur in the Naaldwijk model unit, but its distribution seems to be influenced not only by the sedimentary environment but also by the thickness of the unit (Figure 6.14). To understand in which depth range the loose sand can primarily be found, we analysed the occurrence of loose sands in depth intervals of 5 m.

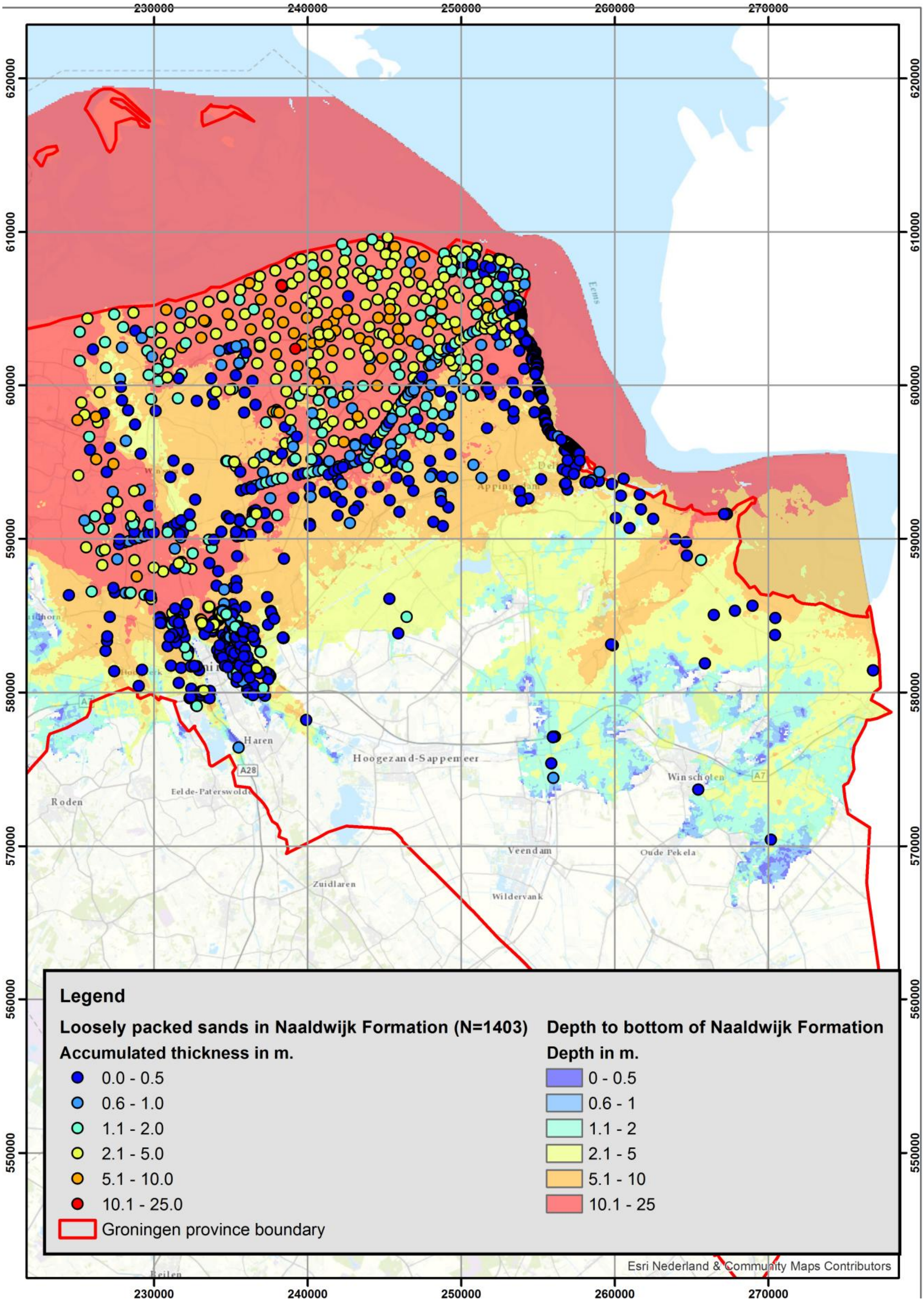

Figure 6.14 *Accumulated thicknesses of loose sands in the entire Naaldwijk model unit and the apparent relationship with the unit's thickness*

Figure 6.15 to Figure 6.18 show the distribution of loose, medium dense and dense sands in the depth ranges between 0 - 5m, 5 - 10m, 10 - 15m and 15 - 20 m below the surface. Figure 6.19 shows the statistics for these depth ranges in a bar chart.

In the depth range between 0 and 5 m (Figure 6.15), the total thickness of sand is low in the thinner parts of the Naaldwijk unit. This is due to the dominance of clay and loam in this part of the extent, related to its more proximal (close to land) environment.

In the depth range between 5 and 10m (Figure 6.16), the total thickness of loose and medium dense sands is increasing. The dense sands are mainly concentrated in the CPTs in the north, and almost absent in the central area.

In the depth range between 10 and 15 m (Figure 6.17), dense sands remain relatively rare in the central area. In the area northwest of Groningen, the share of dense sands is increasing.

Finally, in the depth range between 15 and 20m (Figure 6.18), only in a few areas CPTs reach to this depth. The medium dense and loose sands are still in the majority compared to the dense sands (Figure 6.19).

The depth range between 20 and 25m only shows several CPTs with thin intervals of loose sand and is not shown.

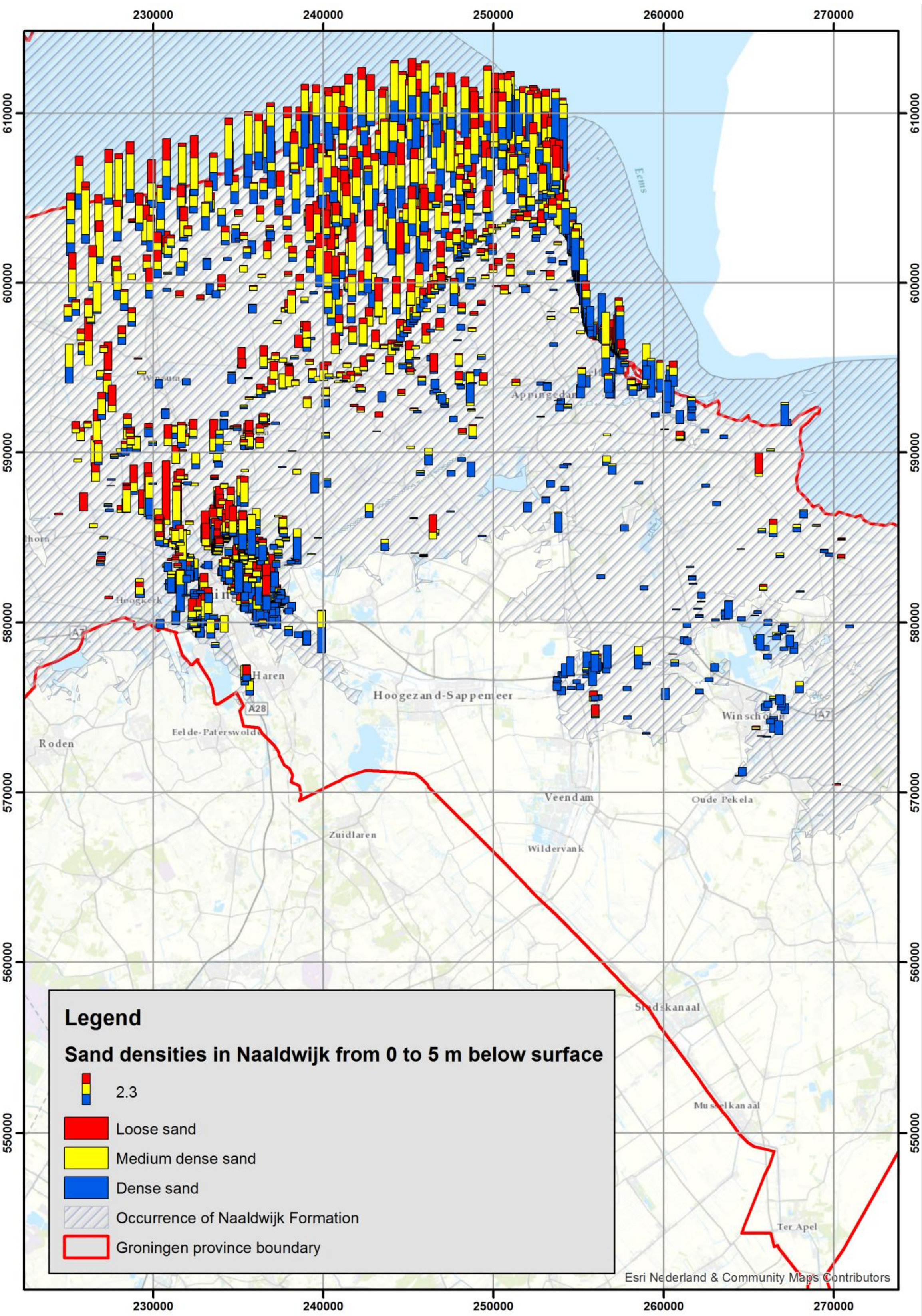

Figure 6.15 *Stacked bars showing the ratios between loose, medium dense and dense sand thicknesses in the Naaldwijk unit in depth zone 0 – 5m. A thickness scale (2.3) is given in the legend, expressed in m*

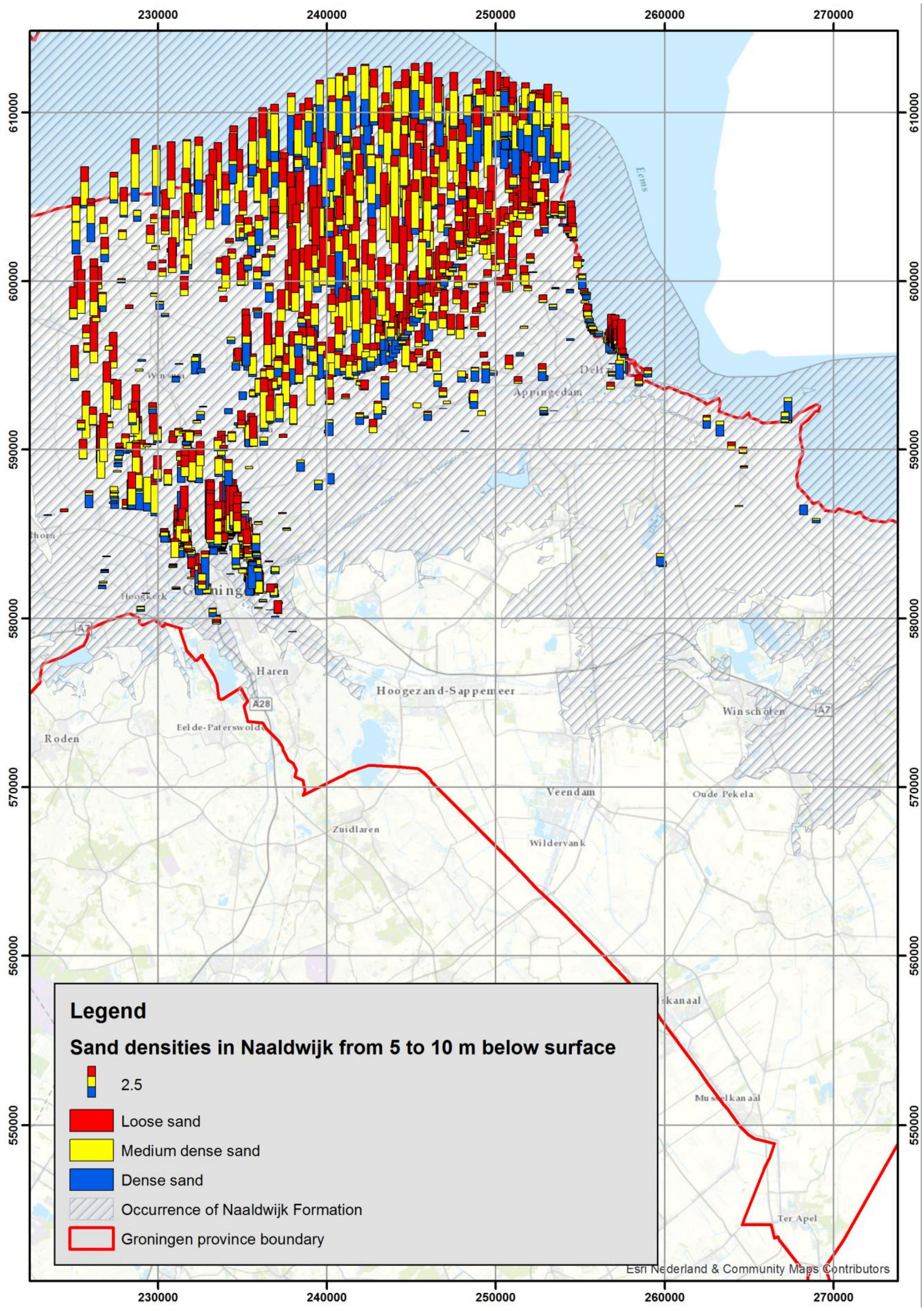

Figure 6.16 Stacked bars showing the ratios between loose, medium dense and dense sand thicknesses in the Naaldwijk unit in depth zone 5 – 10m. A thickness scale (2.5) is given in the legend, expressed in m

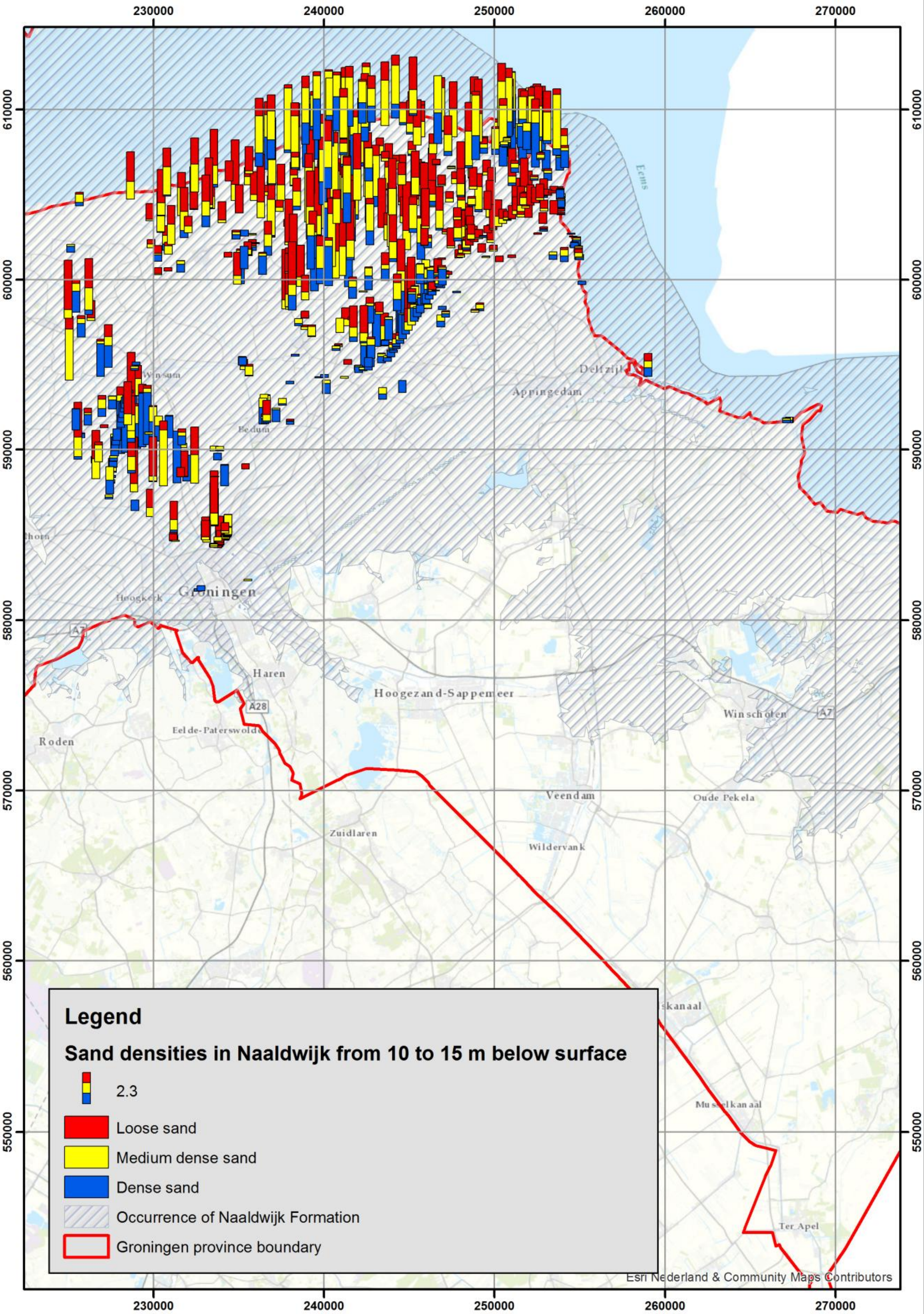

Figure 6.17 Stacked bars showing the ratios between loose, medium dense and dense sand thicknesses in the Naaldwijk unit in depth zone 10 – 15m. A thickness scale (2.3) is given in the legend, expressed in m

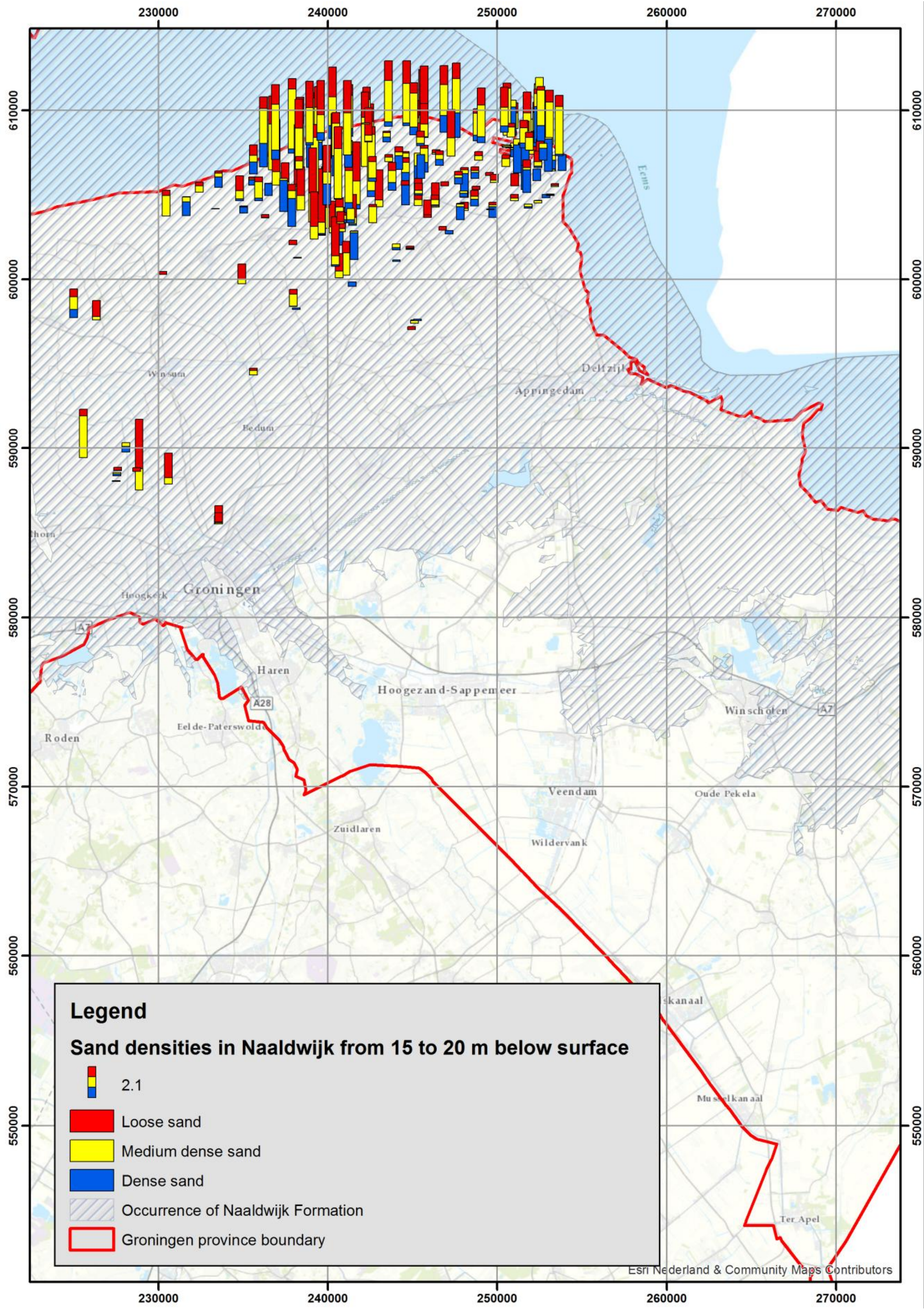

Figure 6.18 Stacked bars showing the ratios between loose, medium dense and dense sand thicknesses in the Naaldwijk unit in depth zone 15 – 20m. A thickness scale (2.1) is given in the legend, expressed in m

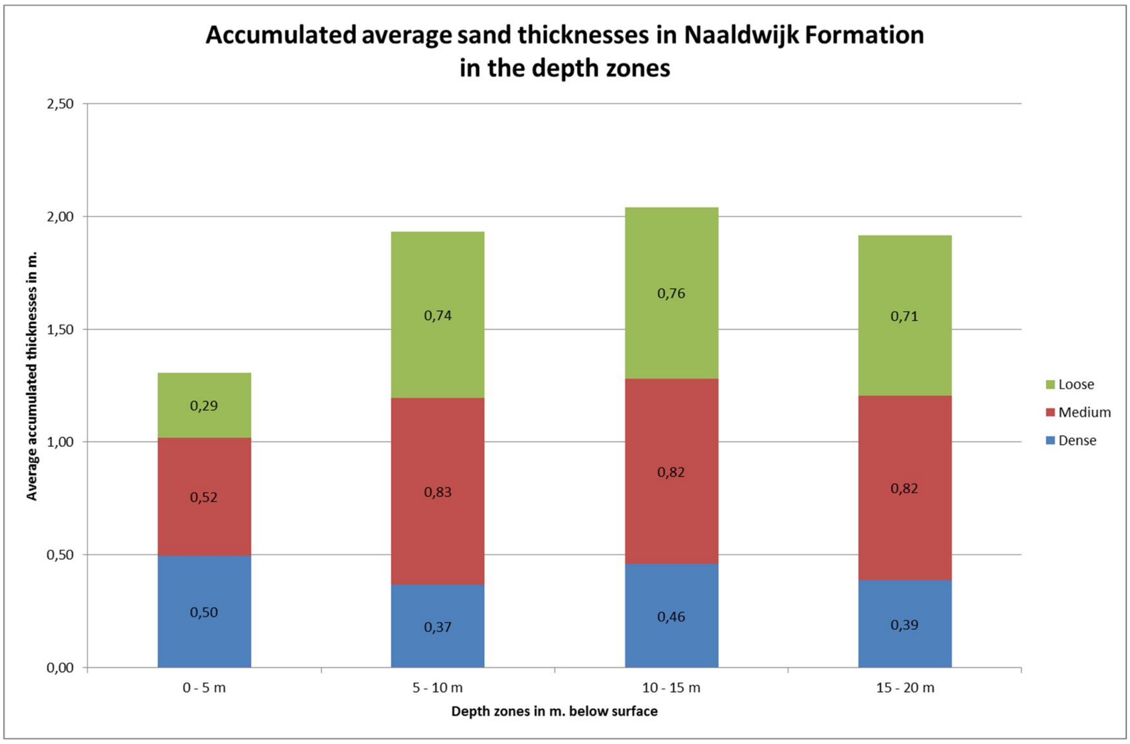

Figure 6.19 Bar chart showing the average thickness of loose, medium dense, dense sands in the Naaldwijk unit for the four depth ranges considered

6.6 Relative sand density for the different geological units

So far the focus was on the relative sand density for the Naaldwijk unit and combined Pleistocene units between 0 and 20 m below the surface, and the units between 20 and 40 m below the surface. These analyses show a higher contribution of loose sands in the Naaldwijk unit, and less so for the Pleistocene geological units. However, locally there is a larger contribution of loose sands in the Pleistocene units as well. To assess whether these anomalies can be attributed to specific units in the Pleistocene, here we compare the relative contributions of the sand categories for the different units (Figure 6.20).

The figure shows that the marine geological units, Naaldwijk and Eem, have the largest contribution of loose sands. In the older units, the contribution of loose sands drops to around 10%. Only the Urk unit, which may also have a marine influence, the contribution is still almost 20%. It must be said however, that the sand bodies of the Naaldwijk and Eem units can contain cm scale clay beds which may influence the assignment of the sand categories.

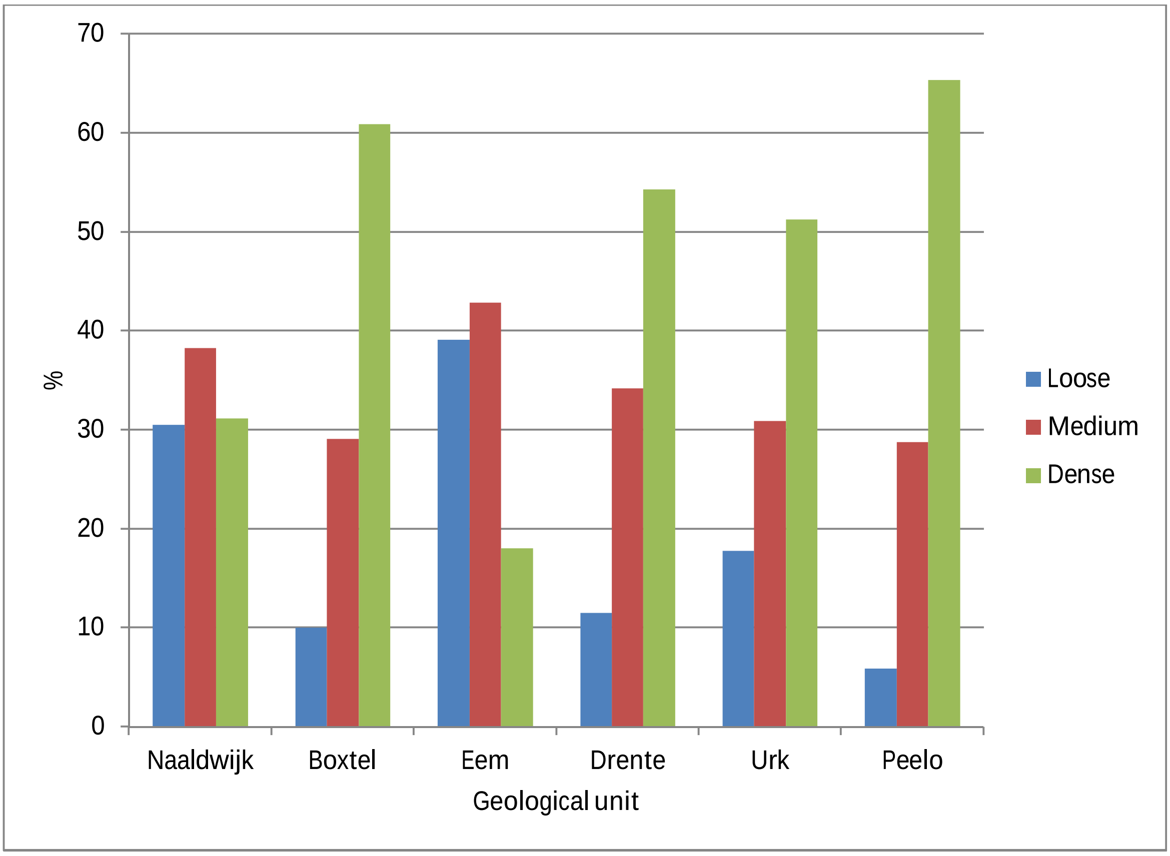

Figure 6.20 Relative contributions of loose, medium dense and dense sands for the considered geological units

7 Quality check: comparison between sand thickness derived from CPTs and as published by GeoTOP

A comparison is made between the total thickness of the loose, medium dense and dense sands as derived from the CPTs and the sand thickness modelled in the GeoTOP OostWadden model. The sand thickness from GeoTOP is based on interpolated DINO borehole lithological logs. Although these two methods are entirely different, they should produce more or less the same results. In this case a comparison is made based on the sand thickness in the Naaldwijk unit. Figure 7.1 shows the CPT locations with the total sand thickness of loose, medium dense and dense sands as an overlay on the GeoTOP map of total sand content in the Naaldwijk unit. A statistical comparison is shown in Figure 7.1 displaying the differences in sand thickness at the CPT locations.

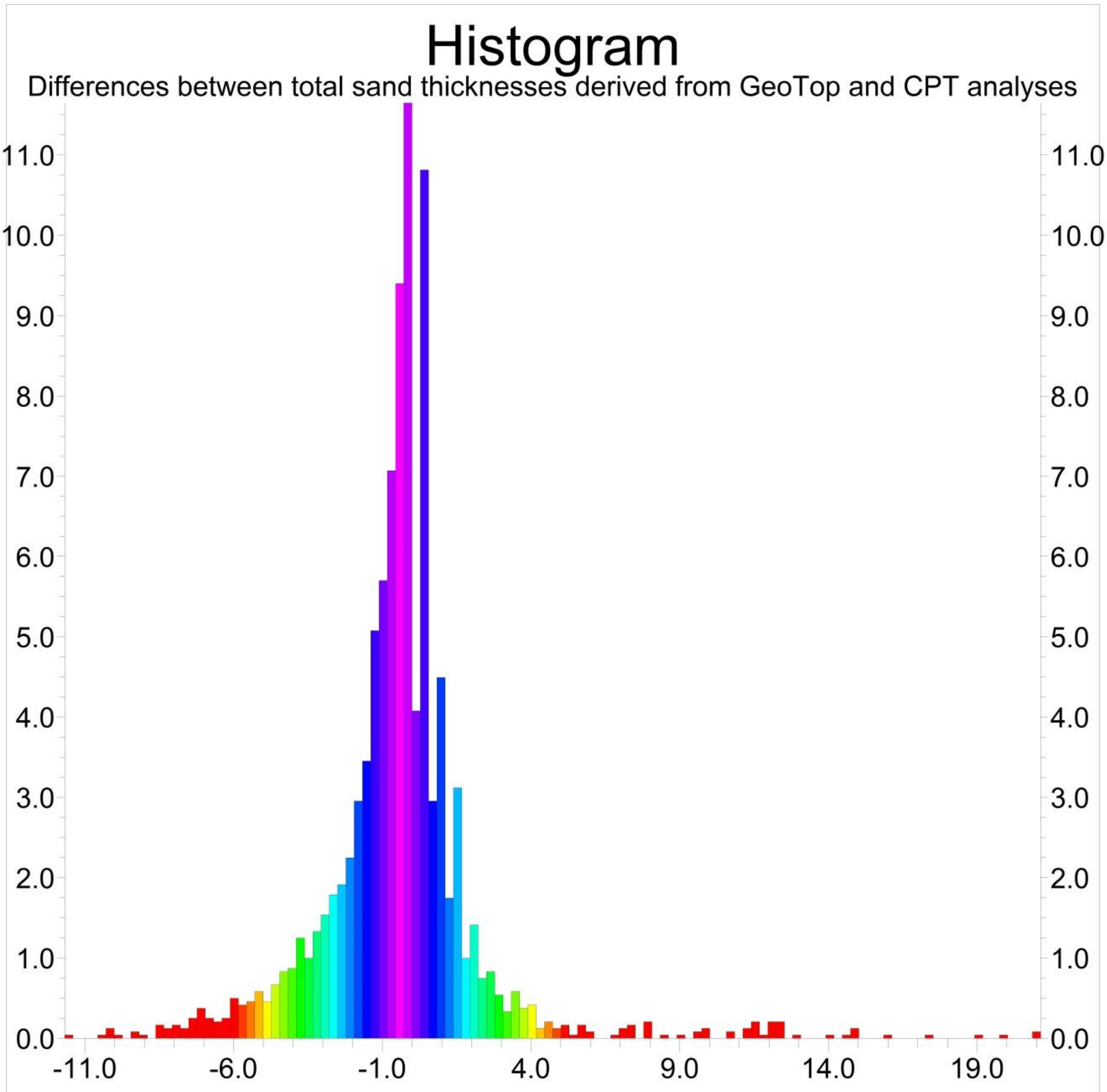

Figure 7.1 Histogram of the difference between total sand thickness derived from CPTs compared with GeoTOP data in the Naaldwijk unit

The sand thickness derived from the CPTs matches the thickness variations of the GeoTOP data. Also the scarcity of CPTs in the area north of Groningen city where GeoTOP interprets absence of sandy layers seems to match closely. This also applies to the area farther to the east, roughly from Loppersum to Delfzijl.

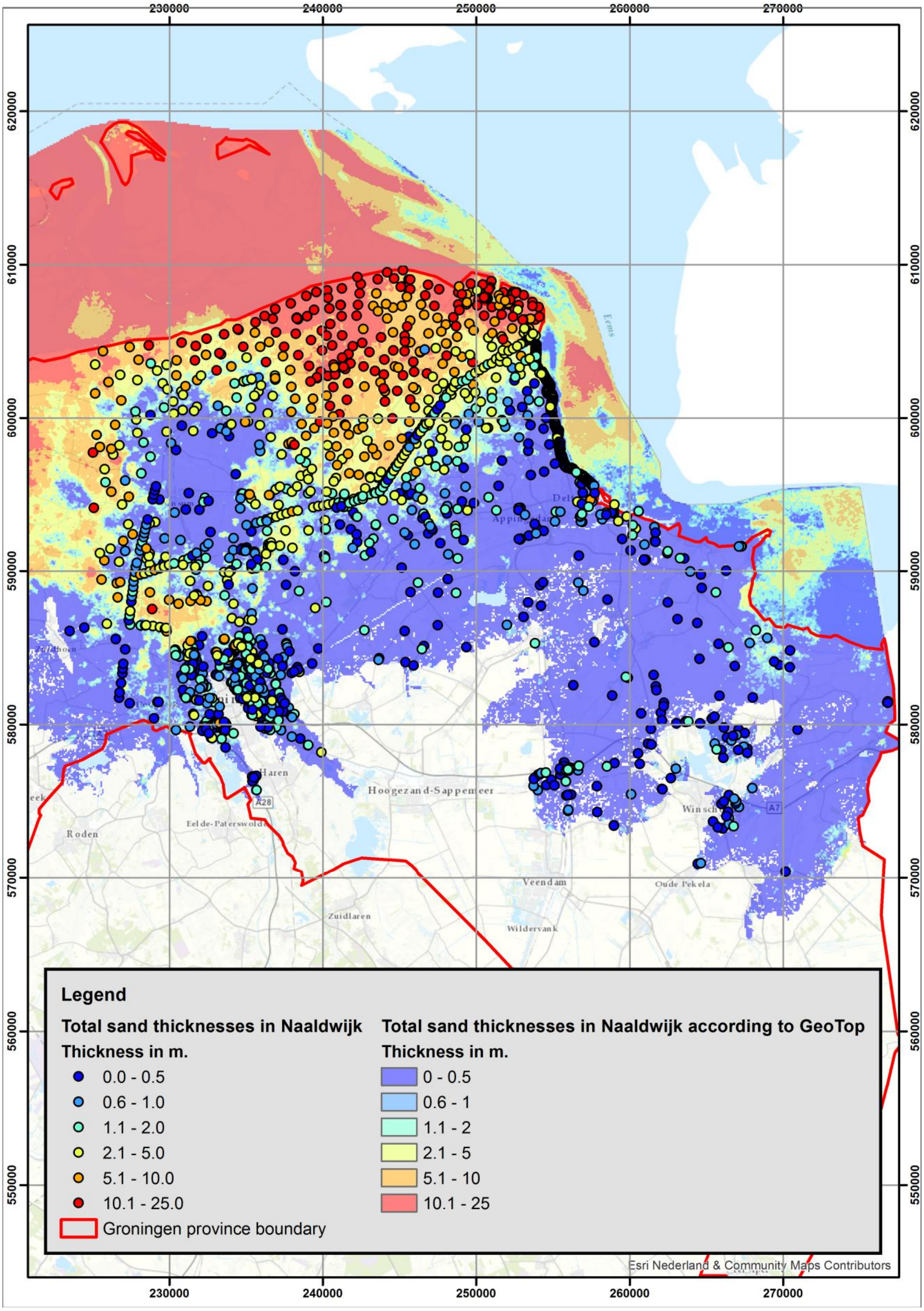

Figure 7.2 Comparison between the total sand thicknesses (loose, medium dense and dense together) and the total accumulated sand thickness in the Naaldwijk unit according to the GeoTOP model

8 Conclusions concerning the spatial distribution of relative sand densities

One of the risk items related to the Groningen earthquakes is related to the occurrence of liquefaction of sand layers, which may potentially lead to loss of strength of the soil and settlements of surface and structures. This report describes the development of a geological model for the Groningen field area to gain more insight in the occurrence of loose, medium dense and dense sands related to the risk of liquefaction. This liquefaction geological model (GLG) is mainly based on CPTs and on the released version of GeoTOP (from TNO). The GLG-model presented consists of maps defining the distribution of the thickness of loose, medium and dense sand layers based on stratigraphy and lithology. The uniqueness and strength of this study is the amount of CPT data that has been used and the estimation of relative densities attributed to specific geological units and sub-units.

In this model it is assumed that the liquefaction potential can be derived from CPT values. Although several factors (like age, cementation, over consolidation) influence the liquefaction potential, most of these factors will be implicitly included in the CPT values. These aspects for the different geological units in the area are described in detail, so that in the future specific factors could be used to determine a unit-specific liquefaction potential.

The relative density of the soil (based on CPT value and stress level) is presented in this model as the main factor determining the liquefaction potential. Future work needs to determine the link between density and liquefaction potential and the actual risk (with consequences for structures).

The depth ranges considered are 0 to 20m below the surface and 20 to 40m the surface. The ranges are based on a combination of the amount of CPTs available and the potential for liquefaction to cause damage. A sensitivity study has shown that, although most relevant contributions of loose sand layers are expected within the 0 – 20m depth range, in specific areas also loose sand deposits are relevant at deeper levels. These appear to primarily belong to the Eem model unit.

Conclusions based on the findings of the GLG model are:

- The thickest and most extensive deposits of loose sand are found in the Holocene Naaldwijk unit. They can be found in the North of Groningen (close to the Waddenzee) and around the city of Groningen. In the Pleistocene units, mainly the Eem unit stands out in this respect.
- The loose sands can reach accumulated thicknesses of up to 10m (in the first 20 m), but most occurrences are less than 1.5 m thick.
- The spatial distribution of the relative sand densities in the Naaldwijk unit show that the thickest occurrences can be related to deep marine (tidal) channel deposits in the north of the area.
- The loose sands thickness in the Naaldwijk unit can be grouped into zones based on the depth of the base of the model unit were used to determine average loose sand thicknesses. The thicknesses of loose, medium dense and dense sands increase considerably from the southern subarea towards the north. The mean of the thickness of the sand deposits (loose, medium and dense together to 20 m below the surface) in the Naaldwijk unit is less than 1 or 2m south of the line from Warfum, Middelstum to

Eemshaven. The total sand thickness increases to almost 20 m close to the Waddenzee.

- A comparison of the considered geological units shows that the Naaldwijk and Eem units show the highest relative amounts of loose sands. In the other units the relative amount of loose sands is generally less than 10%.
- The thickness variations of the total set of loose, medium dense and dense sands closely matches the GeoTOP sand thickness map of the Naaldwijk unit
- The CPT locations in the city area of Groningen show a high variability in occurrence of loose sands for both geological units. There is a significant amount of locations in the city area of Groningen with more than 2.5 m of accumulated thickness of loose sands.
- All Pleistocene units except for the Eem unit contrast strongly with the Holocene Naaldwijk Formation as the medium dense and dense sands are clearly dominating. Loose sands are a minor phenomenon within the Pleistocene units.

9 Recommendations and future developments

Deltares has built a model to evaluate liquefaction potential for areas within the Groningen gas field area (+ 5 km buffer). The spatial distribution of relative sand densities to evaluate the liquefaction potential is based on CPT analyses and clustering according to geologically coherent units. It has been demonstrated in the previous chapters that the geological occurrence of sandy units in the Naaldwijk and Eem Formations appear to be the prime contributors to the amount of (loose) sands.

This geological model can now be used to determine the liquefaction risk based for each formation and location. For all locations where there is currently no CPT available, an estimate can be made based on the geological modelling of the formation limits, the determined sand density distribution for the areas indicated in this report. For a more detailed view additional research can be used to refine the liquefaction risk by filling in the remaining white spots on the map:

- Further delineation and mapping of the sandy channel systems of the Naaldwijk and Eem units.
- Perform additional CPTs in the buried channel systems in the Naaldwijk unit, after the background data of the channel systems has been updated. In particular more CPTs are required in the buried Hunze valley NW of Groningen city.
- Perform additional CPTs in specific areas, especially in those where the Naaldwijk sands occur at deeper levels. This means in general that the subareas with thicknesses of 0-5m and 5-10m, with small accumulated sand thickness and likewise low liquefaction potential, can be disregarded for future CPT location planning. However, an exception should be made for those thin subareas where the Eem unit is found at depth less than 20 m minus NAP and where channel systems are found.
- Perform additional CPTs to deeper levels in potentially vulnerable areas.

The determination of the (relative density of) the sand layers is based on international literature. Validation of these methods for typical Groningen sand layers is recommended:

- The method for the assessment of the relative density should be validated with the deposits present in the study area.
- Use of the Top-Integraal borehole/CPT pairs in the Groningen area to develop a statistical model correlating the CPT parameters with local lithology.

The current geological model and relative soil densities serve as a basis for the liquefaction assessment. Several additional steps need to be taken before this assessment is complete, which is part of the work in the hazard and risk team. This can be done based on current knowledge of the liquefaction behaviour of sands or if this turns out to be to general and/or too complicated, more detailed assessments are possible to further reduce the risk. For these assessments we suggest the following recommendations:

- The relative density of the sand strongly influences the liquefaction potential. A further study could be used to determine the critical thickness of a loose sand layer to become susceptible to liquefaction and to determine whether the liquefaction potential is influenced by intercalation between dense sand layers or clay layers, etc.

- The effect of other factors than the relative sand density that influence the susceptibility to liquefaction should be incorporated, like overlying deposits etc. this can be done in the form of a literature review into the type of sandy deposits and the kind of geological setting that has proven to be susceptible to liquefaction in the recent past. By better understanding the depositional environment, the presence of clay beds, sorting, grain size, age, thickness and type of under- and overlying deposits etc. the liquefaction susceptibility can be assessed more accurately.

It is known that some of the Groningen deposits are extremely variable, with alternating (often) thin layers of sand and clay. These so called tidal deposits are currently classified either by sand or (sandy) clay in the Douglas and Olsen classification system. Often, they are however a combination of both. If classified as sand, the layers show relatively low density because of low CPT values. The liquefaction susceptibility could therefore be overestimated. In case these layers are classified as clay, no liquefaction is expected at all, which could be an underestimation. Also the behaviour of these mixed layers is not known very well. Assuming that these tidal deposits can liquefy is a very conservative approach. Additional testing can be performed to better understand the actual liquefaction risk of these tidal deposits.

- The influence of mm to cm thick clay beds on the relative sand density can be established for example by acquiring high quality CPT next to high quality boreholes, and determine the relationship.
- Tests can be performed in the laboratory to determine the influence of the cone tip resistance (Qc) and Friction factor (Rf) in the 20 cm zones in the top and bottom of a sandy layer and the relation with the total thickness of the sandy layer. This is aimed at assessing correction factors for these biased top and bottom zones, especially when it concerns a number of sand layers.
- Especially for the tidal deposits, the identification of the amount of sand and the density of the sand layers is difficult based on existing correlations. A more detailed investigation of these layers can be made into the classification and density, as well as the liquefaction susceptibility of these layers.
- GCPTs, which stands for Gamma Ray CPTs, can be performed in the tidal deposits of the Naaldwijk Formation to reveal much better the position of clay layers or relative clay/silt contents.

References

Ahmadi, M.M., Robertson, P.K., (2005). Thin-layer effects on the CPT q_c measurement. Can. Geotech. J. vol. 42: pp 1302–1317.

Arango, I., Kramer, C., (1994). The importance of aging on the liquefaction resistance of sand deposits. Proceedings of the NEHRP Conference and Workshop on Research on the Northridge, California Earthquake of January 17, 1994

Berg, P. van den (1994). Analysis of soil penetration. PhD thesis Delft University of Technology.

Bosch, J.H.A., (2000). Standaard Boor Beschrijvingsmethode, versie 5.1. TNO-rapport NITG 00-141-A

Bosch, J.H.A., Harting, R., Gunnink, J.L., 2014. Lithologische karakterisering van de ondiepe ondergrond van Noord-Nederland (Topsysteem hoofdgebied 5) TNO 2014-R10680

Dambrink, R.M., Maljers, D. & Stafleu, J. (2014). Customised geological information derived from multi-purpose 3D voxel models (Abstract). 12th Nederlands Aardwetenschappelijk Congres (NAC12), April 8-9 2014, Veldhoven, The Netherlands. Available at: http://nac12.nl/conference-details/programme/poster/529

Douglas, J. B. and R. S. Olsen (1981). Soil Classification using Electric Cone Penetrometer. Symposium on Cone Penetration Testing and Experience, Geotechnical Engineering Division, ASCE, St. Louis, p. 209-227.

Gassman, S.L., Leon, E., Talwani, P. (2004). A Method to Assess the Liquefaction Potential of Aged Sediments. 13th World Conference on Earthquake Engineering Vancouver, B.C., Canada August 1-6, 2004 Paper No. 2843

Gillins, D.T. (2012). Mapping The Probability and Uncertainty of Liquefaction-Induced Ground Failure, PhD thesis University of Utah, 2012

Ishihara, K., Takatsu, H. (1978). Effects of overconsolidation and K0 conditions on the liquefaction characteristics of sands. Proceedings of the First Caribbean Conference on Earthquake Engineering, Port-of-Spain, Trinidad, 1978

Ishihara, K.(1985). Stability of natural deposits during earthquakes
Proceedings 11th International Conference on Soil Mechanics and Foundation Engineering, 1985, pp 321-376

Kruiver, P., de Lange, G., Wiersma, A.P., Meijers, P., Korff, M., Peeters, J., Stafleu, Harting, R. Dambrink, R., Busschers, F. & Gunnink, J. (2015). Geological schematisation of the shallow subsurface of Groningen - For site response to earthquakes for the Groningen gas field. Deltares Report No. 1209862-005-GEO-0004-v5-r, 16 March 2015, 227 pp.

Leon; E., Gassman, S.L. Talwani, P. (2006). Accounting for Soil Aging When Assessing Liquefaction Potential. Journal of Geotechnical and Geoenvironmental Engineering, Vol. 132, No. 3, March 1, 2006, pp 363-377

Lunne, R., Christoffersen, H.P. (1983). Interpretation of cone penetrometer data for offshore sands. Offshore Technology Conference, paper OT 4464, Houston, USA, May 2-5, 1983

Maljers, D., Dubelaar, W, Stafleu, J., Busschers, F., Dambrink, R. and Schokker, J., 2016. Modelleerwerkwijze GeoTOP modelgebied Oostelijke Wadden en aandachtspunten GeoTOP versie 1.3, stand 11 maart 2016. TNO report 060.21052/01.06-1IV

De Mulder, E.F.J., Geluk, M.C., Ritsema, I., Westerhoff, W.E. & Wong, T.E. (2003) De Ondergrond van Nederland. Geologie van Nederland, deel 7. Nederlands Instituut voor Toegepaste Geowetenschappen TNO, Utrecht. 379 p.

Peels, J. Dijkstra, O. (2010). Funderen in het Hoge Noorden, Overgeconsolideerde grondsoorten in Noord-Nederland spannend. GEOtechniek Funderingsdag 2010 Special – december 2010

Robertson, P. K. (1990). “Soil Classification using the Cone Penetration Test,” Canadian Geotechnical Journal, Vol. 1, No. 27, pp. 151-158.

Schmertmann, J.H. (1978). Guidelines for Cone Penetration Test, Performance and Design, Report No. FHWA-TS-78-209, U.S. Department of Transportation, Washington, D.C., pp. 145.

Stafleu, J., Maljers, D., Gunnink, J.L., Menkovic, A. & Busschers, F.S. (2011). 3D modelling of the shallow subsurface of Zeeland, the Netherlands. Netherlands Journal of Geosciences - Geologie en Mijnbouw 90 - 4, p. 293-310. Available at: https://www.dinoloket.nl/meer-weten-over-GeoTOP

Stafleu, J., Maljers, D., Busschers, F.S., Gunnink, J.L., Schokker, J, Dambrink, R.M., Hummelman, H.J. and Schijf, M.L., 2012. GeoTOP modellering. TNO-rapport TNO 2012 R10991.

Villet, W.C.B., Mitchell, J.K. (1981). Cone resistance, relative density and friction angle.
Proc. of a Session on Cone Penetration Testing and Experience, ASCE National Convention, St. Louis, Missouri, October, pp 178-208.

De Vries, F., de Groot, W.J.M., Hoogland, T., Denneboom, J. (2003). De Bodemkaart van Nederland digitaal; toelichting bij inhoud, actualiteit en methodiek en korte beschrijving van additionele informatie. Wageningen: Alterra (Alterra-rapport 811) - 45 pp (in Dutch).

Vos, P.C., 2015. Origin of the Dutch coastal landscapes. PhD thesis, Utrecht University

Weerts, H.J.T., Cleveringa, P., Ebbing, J.H.J., De Lang, F.D. & Westerhoff, W.E. (2000) De lithostratigrafische indeling van Nederland – Formaties uit het Tertiair en Kwartair. TNO-rapport NITG-00-95-A, 38 p.

Youd, T.L., and Perkins, D.M. (1978). Mapping liquefaction-induced ground failure potential, Journal of the Geotechnical Engineering Division 104, No. GT4, 433-446.

Youd, T., Idriss, I., Andrus, R., Arango, I., Castro, G., Christian, J., Dobry, R., Finn, W., Harder, L., Jr., Hynes, M., Ishihara, K., Koester, J., Liao, S., Marcuson, W., III, Martin, G., Mitchell, J., Moriwaki, Y., Power, M., Robertson, P., Seed, R., and Stokoe, K., II (2001). Liquefaction resistance of soils: Summary report from the 1996 NCEER and 1998 NCEER/NSF workshops on evaluation of liquefaction resistance of soils. J. Geotech. Geoenviron. Eng., 127 (10), 817–833.

A Detailed lithological description of geological units in the shallow subsurface above the Groningen field

A Detailed lithological description of geological units in the shallow subsurface above the Groningen field

This appendix describes all sandy lithostratigraphic units that are present in the shallow subsurface of the northern Netherlands that are potentially susceptible for liquefaction, and the characteristics of the lithofacies that can be distinguished within these units. The overview serves to help assess the susceptibility of different geological units and lithofacies to liquefaction and focuses on the upper 40 m within area of the Groningen gas field including a buffer of 5 kilometers.
For all stratigraphic units, the origin and approximate age are described, as are the thickness and depth of the base of the unit. Distinguished Members and Beds, and different lithofacies within these units are also characterised separately. Statistic data provided in this overview include median percentages of the lithologies clay, silt, sand and organic components in both the stratigraphic units and lithofacies.
All statistic information originates from the report TNO 2014-R10680 'Lithologische karakterisering van de ondiepe ondergrond van Noord-Nederland (Topsysteem hoofdgebied 5)' by Bosch et al. (2014) and attachments, which covers the results of a high resolution drilling campaign (TopIntegraal research programme) executed by TNO – Geological Survey of the Netherlands. Hence, this appendix provides a translated excerpt of the report delivered by TNO.

N.B. Explanatory notes:

Corings executed within TopIntegraal study
Within the TopIntegraal study, a total of 75 cores with a penetration depth of 15 to 40 meters below surface were taken from the Northern Netherlands, roughly encompassing the provinces of Groningen, Friesland and Drenthe (Figure 1). Of these 75 boreholes, only 12 are actually situated within the Groningen study area. The following descriptions, statistics and interpretations are based on the entire area, not only on cores from the GLG model area. At the beginning of every chapter or paragraph on a stratigraphic unit or lithofacies, the cumulative thickness of that unit in all cores in the area is given.

Lithofacies description
As this report serves to help assess the sensitivity of sands to liquefaction in the Groningen gas field area, only lithofacies that contain sand from lithostratigraphic units that can occur within this area are described.
A lithofacies unit is a group of sediment with either more or less similar lithological characteristics or a specific variation in them which makes them identifiable in an undisturbed core. The names are descriptive of a depositional environment that may be associated with the lithofacies, it wasn't necessarily deposited in one.
The following paragraph is a summary of core sample descriptions of all different corings for that lithostratigraphic unit or lithofacies in the Northern Netherlands dataset from the TopIntegraal study. These include the estimated sand median for that lithofacies based on core descriptions (average). Finally, the results for grain size analyses performed within the TopIntegraal study are presented. Sand medians may deviate from those in the core descriptions.
Information that is provided is only a selection of information available within the TopIntegraal study. For more results of this study, please consult the TNO report 'TNO 2014-R10680

Lithologische karakterisering van de ondiepe ondergrond van Noord-Nederland (Topsysteem hoofdgebied 5) including the (digital) attachments.

For the description of the sediment characteristics, the NEN 5104 standards are used and the definitions of the general borehole description manual by TNO (Bosch, 2000; **Error! Reference source not found.**):

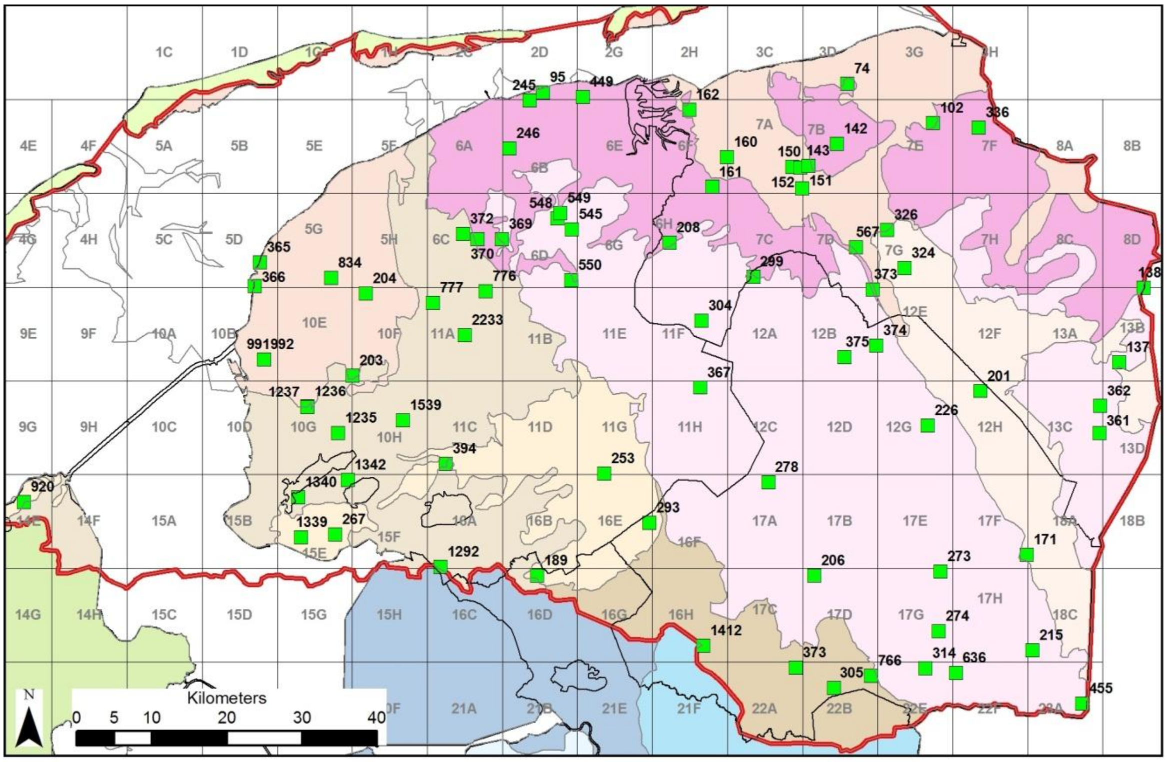

Figure 1. Overview of TopIntegraal borehole locations in Northern Netherlands.The background colours indicate subareas that are not discussed in the text (modified after Bosch et al., 2014).

The definitions of the terms used in the text are as follows: described properties are as follows:

Table 1. Overview of standards and definitions used for the general borehole description (Bosch, 2000)

Gravel Admixture	
Slightly gravelly	>0 – 5%
Medium gravelly	≥5 – 15%
Very gravelly	≥15 – 30%

Silt Admixture	
Slightly silty	>0 – 5%
Medium silty	≥5 – 15%
Very silty	≥15 – 30%
Extremely silty	≥30 – 50%

Carbonate content	Response to 10% HCl
Non-calcareous	No response, less than 0.5% CaCO3
Low calcareous	Audible fizzling, >0.5 – <2% CaCO3
High calcareous	Visible fizzling, > 2% CaCO3

Sand uniformity coefficient (Sorting)	CU (D60/D10)
Very well sorted	< 1.8
Well sorted	≥ 1.8 - <2.2
Poorly sorted	≥ 2.2 - <3.0
Very poorly sorted	≥ 3.0

Sand categories	Sand median
Fine	63 – 150 µm
Medium	150 – 300 µm
Coarse	300 – 2000 µm

Sand categories	Sand median (µm)	
Sand extremely coarse (SEC)	≥ 420	< 2000
Sand very coarse (SVC)	≥ 300	< 420
Sand medium coarse SMC)	≥ 210	< 300
Sand medium fine (SMF)	≥ 150	< 210
Sand very fine (SVF)	≥ 105	< 150
Sand extremely fine (SEF)	≥ 63	< 105

A.1 Naaldwijk Formation

A.1.1 Genesis

During the Holocene, sea level rise resulted in the formation and subsequent drowning of the basal peat of the Nieuwkoop Formation. In Groningen, this led to the formation of a large lagoon (with rooted muds). Continuing sea level rise led to further drowning of the land, and the lagoon was replaced by a mudflat environment, in which tidal channels, tidal flats and eventually salt marshes developed.

A.1.2 Members and Beds and Beds

The Naaldwijk Formation can be subdivided into two members, based on the presence of an intercalated peat layer (Hollandveen Mb., Nieuwkoop Fm.). Below the peat layer lies the older Wormer Member. The younger Walcheren Member covers the peat. However, in the Northern Netherlands the extent of the peat layer between the younger and older marine deposits of the Naaldwijk Formation is limited. In the GeoTOP Oostwadden model, the distinction is only partly made, whereas all Naaldwijk Fm. sediments are grouped together in the TOPINTEGRAAL study of the Northern Netherlands.

A.1.3 Extent

The Naaldwijk Formation occurs in previously low-lying areas, as is implied by its genesis as a former part of the Wadden Sea (Figure A.1). It occurs mainly in the northern half of our study area, the Groningen gas field including a buffer of 5 km, in which it reaches a maximum thickness of approximately 28 meter at the northern end.

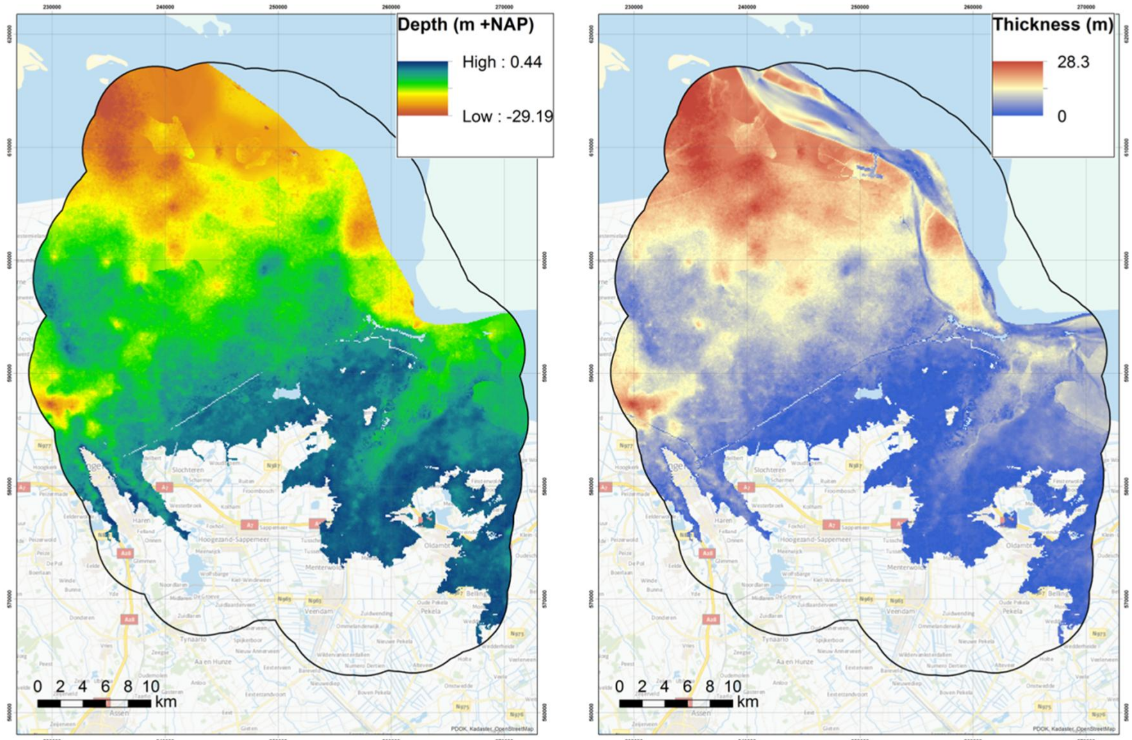

Figure A.1 Depth of the base (left) and total thickness (right) of the Naaldwijk model unit from GeoTOP (Maljers, et al., 2016).

A.1.4 Lithology

The lithological characteristics of different lithofacies are described separately in the following paragraphs. An overview of results of grain size analysis for all lithofacies combined can be found in Table A.1.

Table A.1 Results of the grain size analyses on the Naaldwijk Formation, for all lithofacies combined. Compositional percentages and sand characteristics (sand median and uniformity coefficient) are median values (D50-percentile) of the sample data, shown only if 5 or more analyses have been performed.

Lithology	Analyses (n)		Fractions(%)				Sand characteristics	
Sand cat.	Grain size	Org. comp.	Lutum	Silt	Sand	Organic matter	Sand Median (µm)	CU
Clay	142	139	18.19	51.71	28.17	2.5	94.5	1.5
Loam	52	52	13.6	62.05	24.12	2.65	88.59	1.45
Sand	102	95	2.01	9.52	87.77	0.87	121.73	1.61
Sand fine	76	72	3.11	13.25	83.77	1	116.72	1.59
Sand medium	21	19	0	0.97	99.03	0.42	195.39	1.71
Sand coarse	5	4	0	0.01	99.99		308.37	1.74

A.1.5 Lithofacies

Lithofacies that have been distinguished in the Naaldwijk Formation are:

- Tidal channel deposits (fine and medium sand)
- Tidal flat deposits (fine sand, clay and loam)
- *Lagoonal deposits (clay, loam and sand)*
- *Supra-/intratidal deposits, salt marsh deposits (clay and loam)*

Lithofacies printed in *italic* are not discussed in this report, due to their low sand content.

A.1.5.1 Naaldwijk Formation - tidal channel deposits

This lithofacies has been encountered in 8 out of 75 of the TopIntegraal cores in the northern Netherlands, with a cumulative thickness of 35 meters in 93 intervals. The thickest occurrence of tidal channel deposits in a core description is recovered from the Hunzedal valley, where it reaches a thickness of 12 meters. The sediments have been deposited under a high energetic environment. The diurnal change in direction of the tidal current can lead to specific intercalations of sand and clay.

These tidal channel deposits often have an erosive base, and lay on Pleistocene deposits, on a different facies of the Naaldwijk Formation or on the Basal Peat Member (Nieuwkoop Formation).

A.1.5.2 Core descriptions

Almost 90% of the marine tidal channel deposits have been described as sand. The remaining material consists of clay, and occasionally loam and shell layers occur. The slightly silty sand has a sand fraction of 97%, with an average estimated sand median of 152 µm. The sorting of the sand varies from very well sorted to well sorted. The sand is moderately rounded and has a greenish grey to green colour. All layers are calcareous and contain at least traces of shells and glauconite grains. In 75% of the layers, small amounts or traces mica have been found.

In 60% of the descriptions, sand has been described as bedded with other lithologies; in half of the descriptions clayey layers are mentioned, while the other half involve detrital layers.
The number of described clay layers, intercalated with sand layers is small. The clay is moderately to very silty and contains on average 29% clay fraction. Only little mica has been described in these layers, and no glauconite. Bedding of the clay layers mainly consists of thin layers of detritus.

A.1.5.3 Grain size analysis

Results of grain size analyses that have been performed can be found in Table A.2. Clay samples are extremely silty and slightly humic, with a high sand content mainly composed of the extremely fine (54%) or the very fine (22%) sand median class.
Sand samples are slightly silty and slightly humic. The most important median classes are very fine sand (30%) and moderately fine sand (23%). Compared to tidal channel deposits from the Eem Formation, these sands are finer in general and have a lower contribution from the very coarse and extremely coarse sand median classes.
Sands from all three categories, fine, medium and coarse, is slightly silty and slightly humic and is well sorted. Sand from the fine category contains mostly sand within the very fine sand median class (42%) with extremely fine and medium fine sand (26 and 23%, respectively). The most important sand median classes in the medium category is medium coarse (36%) and medium fine (31%) sand. Most of the sand in the coarse category belongs to the sand median classes medium coarse (32%), very coarse (30%) and extremely coarse (23%) sand.

Table A.2. Results of grain size analysis on the Naaldwijk Formation, tidal channel deposits. Compositional percentages and sand characteristics (sand median and uniformity coefficient) are median values (D50-percentile) of the sample data, shown only if 5 or more analyses have been performed.

Lithology or	Analysis (n)		Median (%)				Sand Median	
Sand cat.	Grain size	Org. comp.	Clay	Silt	Sand	Organics	D50 (µm)	Spread
Clay	7	7	15.1	43.4	41.51	2.14	101.08	1.59
Sand	38	36	0.55	3.64	95.77	0.44	156.08	1.65
sand fine	18	18	1.14	4.62	94.34	0.53	127.17	1.6
sand medium	15	14	0	0.97	99.03	0.42	214.51	1.7
sand coarse	5	4	0	0.01	99.99		308.37	1.74

A.1.5.4 Naaldwijk Formation - tidal flat deposits

The tidal flat facies is the most common lithofacies of the Naaldwijk Formation along the cored transects of the TopIntegraal study. It has been encountered in 16 cores and has a cumulative thickness of 76.67 meter. A total of 65.60 meter has been described in detail in 175 intervals.

A.1.5.5 Core descriptions

According to core descriptions, approximately 60% of the tidal flat sediments consist of sand, while the remaining 40% consist of clay. All sand intervals described in this lithofacies are composed of fine sand with an average estimated sand median of 110 µm and are well sorted. These sand intervals consist of 94% sand fraction, with 1% clay, 5% silt and 1% organic fractions. The sand is moderately rounded and has a greenish grey to grey colour. The sand is calcareous and approximately 90% of the sand contains mica, traces of glauconite and traces of shells. Occasionally, larger amounts of shells or shell layers with a thickness of 4 to 30 cm are present. About 75% of the sand intervals are bedded, with intercalated detritus and, to a lesser extent, clay beds.

According to core description, the clay intervals contains approximately 30% clay fraction and has a moderately firm consistency. It is calcareous and about half of the intervals contain traces of shells and more than half contain mica. It has a greenish grey to olive grey colour, although brown shades can occur close to the surface. Approximately 40% of the clay contains beds, mainly sand beds and, to a lesser extent, detritus beds.

A.1.5.6 Grain size analysis

Results of the grain size analyses can be found in Table A.3. The tidal flat lithofacies in the Naaldwijk Formation have a different sand to clay ratio than its tidal channels as the flats contain relatively more clay. The sand samples in this lithofacies have relatively high clay and silt fractions with a median sand fraction of only 83%. Most sand is of the fine category, with a sand median of 115 µm and very well sorted (1.6). It consists mainly of the extremely fine (40%) and very fine (36%) sand median classes. Medium to extremely coarse sand is a minor contributor (6%). Loam samples are very sandy, slightly humic, and have remarkably high clay content. The sand fraction consists of very fine sand and is very well sorted (1.4). Clay samples are extremely silty and slightly humic. The admixed sand very well sorted (1.5) and consists mainly of extremely fine and very fine sand.

Table A.3 Results of grain size analysis on the Naaldwijk Formation, tidal flat deposits. Compositional percentages and sand characteristics (sand median and uniformity coefficient) are median values (D50-percentile) of the sample data, shown only if 5 or more analyses have been performed.

Lithology or	Analysis (n)		Median (%)				Sand Median	
Sand cat.	Grain size	Org. comp.	Clay	Silt	Sand	Organics	D50 (µm)	Spread
Clay	51	49	12.46	38.00	50.89	1.72	98	1.52
Loam	9	9	16.26	64.72	23.56	1.62	88.36	1.43
Sand	57	52	3.47	13.46	83.08	1.2	115.61	1.6
sand fine	52	48	3.58	13.79	81.91	1.2	114.6	1.6
sand medium	5	4	0	0.75	99.25		176	1.71

A.2 Boxtel Formation

A.2.1 Genesis

Local depositional processes have redistributed sediment since the late Saalian. The sediments interpreted as the Boxtel Fm. and its members were formed in a large variety of depositional environments. This lead to a heterogeneous geological unit of locally derived and deposited material, including various types of aeolian deposits, small-scall fluvial deposits, slope deposits, lacustrine deposits and organic deposits. Sediments of Weichselian or older age may be disturbed as a result of cryoturbation. Deposits date to the Late Saalian until the present day.

A.2.2 Members and Beds

Within the Boxtel Formation, every member is dominated by a certain type of genesis. In the Northern Netherlands, the Wierden Member (dry aeolian coversands), Kootwijk Member (more recent aeolian deposits often related to human activity), Singraven Member (brook valley deposits), and the Tilligte Member (bedded lake and abandoned channel deposits) have been distinguished. Other (local) deposits in the northern Netherlands have been grouped as undifferentiated Boxtel Formation. Within the TopIntegraal project, the Singraven Member and Kootwijk Member have only been recognised in one borehole, and thus have also not been considered separately.

A.2.3 Extent

The Boxtel Formation has been encountered in 67 out of 75 borings within the TopIntegraal study of the Northern Netherlands, with a cumulative thickness in these cores of 329 meters (Figure A.2). In the Hunze valley, a sand interval between the Drente Formation and the Eem Formation is also considered as a part of the Boxtel Formation as it is composed of locally derived deposits and not related to fluvioglacial (Schaarsbergen Mb., Drente Fm.) or marine (Eem Fm.) processes. In the GeoTOP Oostwadden model, these sediments have been incorporated in the Drente model unit for modelling purposes. The lower part consists of local deposits dating back to the Saalian, whereas the upper part of the formation was formed during the Weichselian.

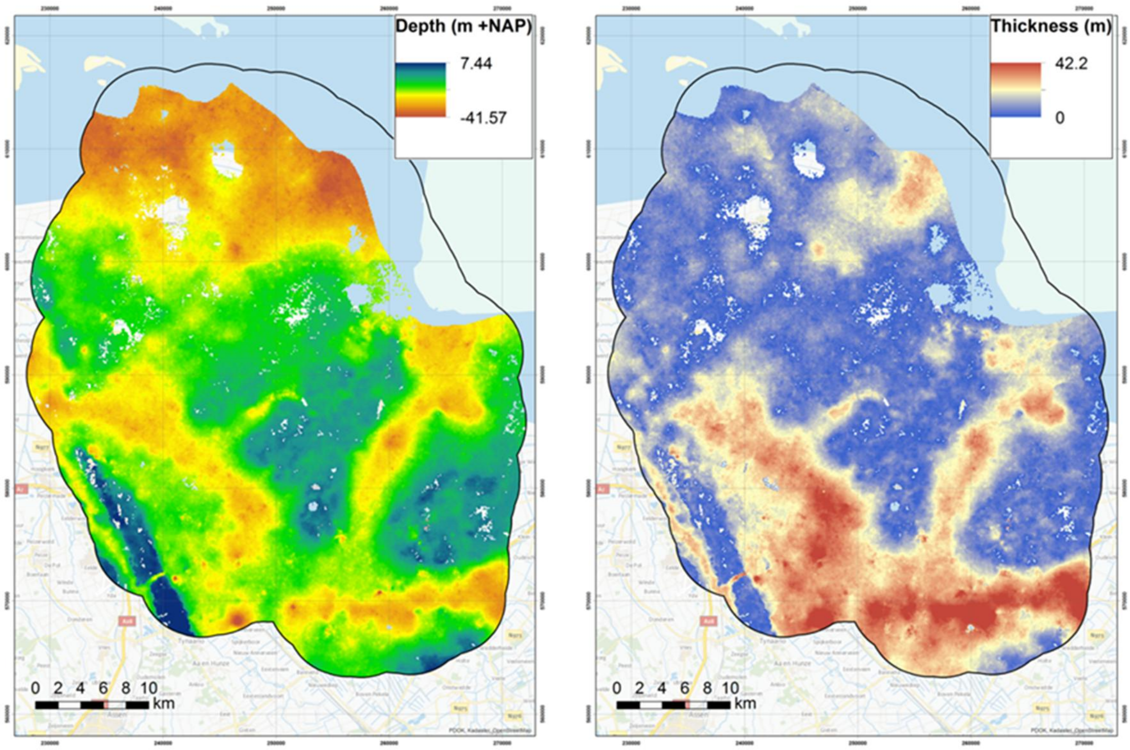

Figure A.2 Depth of the base (left) and thickness (right) of the Boxtel GeoTOP model unit (Maljers, et al., 2016) in the Groningen gas field + 5km buffer.

A.2.4 Lithology

An overview of results of grain size analyses for the undifferentiated Boxtel Formation, the Tilligte Member and the Wierden Member can be found in Table A.4, Table A.5 and Table A.6 respectively.

Table A.4. Results of grain size analysis on the Boxtel Formation, undifferentiated sediments. Compositional percentages and sand characteristics (sand median and uniformity coefficient) are median values (D50-percentile) of the sample data, shown only if 5 or more analyses have been performed.

Lithology or	Analysis (n)		Median (%)				Sand Median	
Sand cat.	Grain size	Org. comp.	Clay	Silt	Sand	Organics	D50 (µm)	CU
Peat	7	10	3.76	21.43	23.99	35.1	120.36	2.06
Clay	24	24	13.3	39.21	45.82	1.76	153.52	2.28
Loam	14	13	7.65	57.43	34.46	5.65	95.52	1.62

Sand	325	296	0.19	2.61	96.77	0.38	204.47	1.99
sand fine	30	30	1.37	15.42	81.57	0.73	128.63	1.77
sand medium	254	230	0.28	2.71	96.73	0.38	201.78	2.01
sand coarse	41	36	0	0.09	99.91	0.27	366.02	1.94

Table A.5 Results of grain size analysis on the Boxtel Formation, Tilligte Member. Compositional percentages and sand characteristics (sand median and uniformity coefficient) are median values (D50-percentile) of the sample data, shown only if 5 or more analyses have been performed.

Lithology or	Analysis (n)		Median (%)				Sand Median	
Sand cat.	Grain size	Org. comp.	Clay	Silt	Sand	Organics	D50 (µm)	CU
Peat	8	12	4.09	16.44	23.83	41.77	181.88	2.83
Clay	44	43	16.64	46.31	39.39	3.78	120.33	1.88
Loam	30	30	10.89	59.58	27.59	4.11	96.56	1.57
Sand	62	60	1.29	6.51	92.58	0.65	189	2
sand fine	13	13	3.94	13.51	84.59	2.18	121.41	1.71
sand medium	43	42	1.18	5.04	93.84	0.46	195.02	2.05
sand coarse	6	5	0.51	2.2	97.29	0.73	384.4	2.51

Table A.6 Results of grain size analysis on the Boxtel Formation, Wierden Member. Compositional percentages and sand characteristics (sand median and uniformity coefficient) are median values (D50-percentile) of the sample data, shown only if 5 or more analyses have been performed.

Lithology or	Analysis (n)		Median (%)				Sand Median	
Sand cat.	Grain size	Org. comp.	Clay	Silt	Sand	Organics	D50 (µm)	CU
Sand	57	55	0.56	4.38	95.11	0.84	193.13	2.1
sand medium	55	53	0.56	4.36	95.25	0.84	196.29	2.1

A.2.5 Lithofacies

Lithofacies that have been distinguished in the Boxtel Formation are:

- Dry aeolian deposits/cover sands (fine and medium sand), Wierden Mb.
- Wet aeolian deposits (fine and medium sand, loam)
- Channel deposits (fine, medium and coarse sand)
- Levee and crevasse deposits (fine, medium and coarse sand)
- Bedded lake and abandoned channel deposits (fine and medium sand, loam, clay), Tilligte Mb.
- Slope deposits (fine and medium sand, loam)
- *Organic lake and abandoned channel deposits (gyttja, clay and loam)*
- *Swamp deposits (peat), Tilligte Mb.*

Lithofacies printed in *italic* are not discussed in this report, due to their low sand content.

A.2.6 Boxtel Formation, Wierden Member – dry aeolian deposits

Dry aeolian sands, which are stratigraphically linked to the Younger Coversand, comprise approximately 21 meters of the TopIntegraal corings. It occurs over large areas in Groningen, although it can be locally absent (Figure A.3). As a rare feature, peat layers can be found intercalated in the sand of this Member.

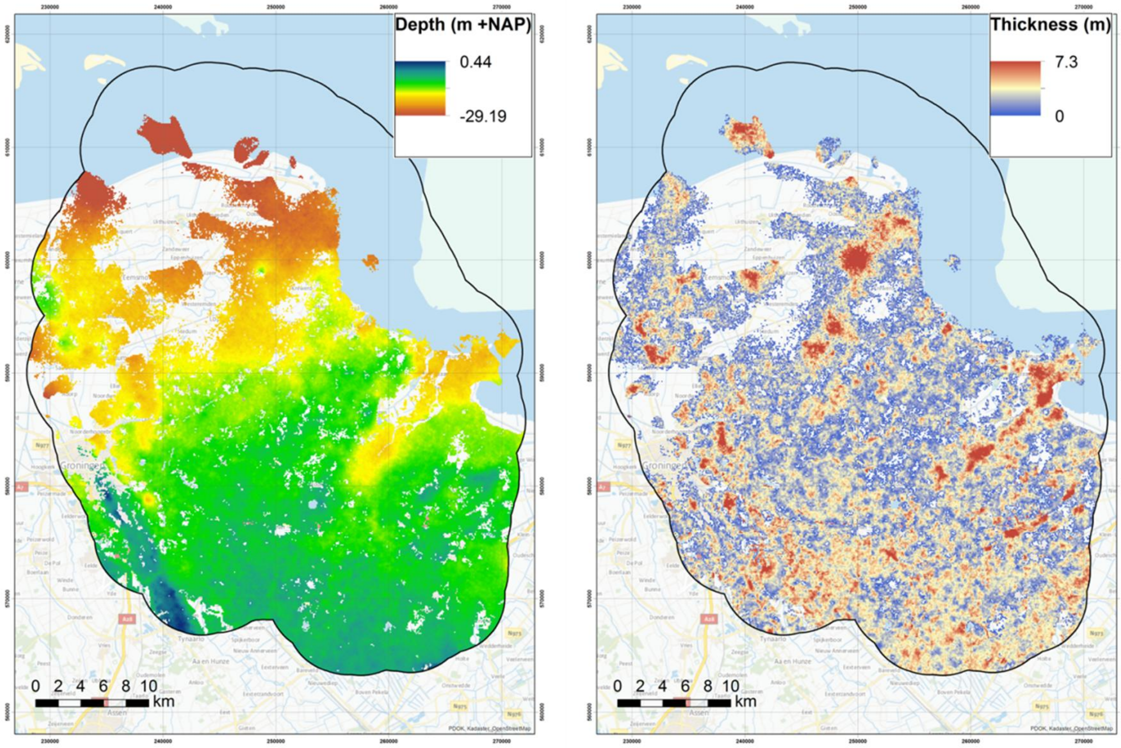

Figure A.3 Depth of the base (left) and thickness (right) of the Wierden Member (Boxtel Formation) GeoTOP model unit (Maljers, et al., 2016) in the Groningen gas field + 5km buffer.

A.2.7 Core descriptions

Coversand is a highly uniform lithofacies. In core descriptions, a sand fraction of over 95% is noted, with an average estimated sand median of 135 µm, moderately sorted, and 4% silt. Sand medians of the fine and medium category are 118 and 174 µm, respectively. The sand is non-calcareous and has a yellowish brown, yellow or brown colour. In about 20% of the intervals of the sand has a bedded character.

A.2.8 Grain size analysis

Results of grain size analysis (Table A.6) show that the sand is slightly silty and slightly humic, with a sand fraction of 95% and a sand median of 193 µm and is well sorted. The most important median classes are medium fine (26%) and medium coarse (29%) sand.

A.2.9 Boxtel Formation – wet aeolian deposits

With a cumulative thickness of 98 meters in 36 out of 75 cores within the TopIntegraal study, this is the most important lithofacies within the undifferentiated Boxtel Formation. A total of 375 intervals have been described in 82 meters of sediment. It consists mainly of sand with sporadic occurrences of clay and loam.

A.2.10 Core descriptions

Wet aeolian deposits are highly similar to the dry aeolian deposits of the Boxtel Formation – Wierden Member. They consist of non-calcareous, slightly silty sands (fraction: 95%) with a median of 148 µm. Sorting in the grain size distribution of analysed samples varies from well to poorly sorted, and occasionally very poorly sorted. In 10% of the sand layers, traces of mica are present, while 17% contains traces of glauconite.

The main difference of dry aeolian deposits and wet aeolian deposits in the Boxtel Formation, is the presence of loam layers in the latter lithofacies, which make up approximately 9% of the sediment. Of these loam layers, 30% contains mica, 10% contains traces of mica and 17% contain traces of glauconite. Loam varies in colour from grey and green to olive grey. Shades of brown also occur. The loam is moderately firm.

In 45% of the sand layers (and 30% of the loam layers), sedimentary bedding is described. A few thin detritus beds, coarse sand and clay layers are observed. Also in the loam layers, sand is described., whereas in 13% of the sand layers loam beds are described.

A.2.11 Grain size analysis

Grain size analyses (Table A.) show that clay layers are highly silty and slighty humic. Part of the samples have a high sand content compared other clays in aeolian, fluvial or marine facies. The sand in the clay samples is medium fine and has a moderate spread. The sand falls within the median classes extremely fine (33%), medium coarse (18%), very fine (16%) and medium fine sand (16%).

Loam in this lithofacies is slightly humic and very sandy, with the admixed sand primarily composed of the extremely fine sand median class (53%) but also contain 12-13% of the very fine to medium coarse classes.

Sand samples are slightly silty, slightly humic, have a median of 194 µm and are well sorted. The most important median classes are medium fine (26%) and medium coarse (26%). All three categories of sand occur, but most sand falls within the medium category, which is slightly silty and slightly humic. Medium fine and medium coarse sand are the most important sand median classes (27% each). The coarse sand category consists mostly of sand from the very coarse median class (30%) but also contains medium coarse and extremely coarse grains (each 25%), and is moderately sorted.

Table A.7. Results of grain size analysis on the Boxtel Formation, wet aeolian deposits.

Compositional percentages and sand characteristics (sand median and uniformity coefficient) are median values (D50-percentile) of the sample data, shown only if 5 or more analyses have been performed.

Lithology or	Analysis (n)		Median (%)				Sand Median	
Sand cat.	Grain size	Org. comp.	Clay	Silt	Sand	Organics	D50 (µm)	CU
Clay	9	9	11.11	42.91	45.05	0.89	153.55	2.44
Loam	6	5	11.31	52.24	36.8	1.00	100.28	1.81
Sand	166	154	0.17	3	96.61	0.39	194.39	2.04
sand fine	14	14	1.40	11.64	86.96	0.65	132.15	1.89
sand medium	147	135	0.11	2.75	96.76	0.39	196	2.06
sand coarse	5	5	0.00	0.09	99.91	0.35	331.34	2.2

A.2.12 Boxtel Formation – channel deposits

Fluvial channel deposits of the Boxtel Formation have a total thickness of about 6 meters and was found in 13 out of75 cores. For 50 meters, 192 intervals with this lithofacies have been described.

A.2.13 Core descriptions

Except for a limited amount of loam layers, fluvial channel deposits of the Boxtel Formation consist almost entirely of sand (sand fraction: 98%, with a median of 177 µm). Most sediment is non-calcareous, although thin calcareous intervals do occur. The facies consists of slightly silty sands from the categories fine (median: 125 µm), and medium (196 µm) and coarse (383 µm, less than 10% of all samples). The coarsest material has been found at the base of the Weichselian infill of the Hunzedal, on top of lacustrine deposits of the Boxtel Formation which superpose a fine-grained Eemian deposit. In 12% of the layers, mica occurs, whereas traces of glauconite occur in almost 30% of the described layers. More than half of the sand intervals contain internal bedding. In addition, detritus and occasionally loam in thin beds in 15% of the described layers. Also few sublayers occur, 9% of which consist of detritus and 6% of loam.

A.2.14 Grain size analysis

Similar to the core descriptions, grain size analyses (Table A.) show that this lithofacies consists almost entirely of sand. One sample was classified as peat, but this represents reworked material that is part of the channel deposits, i.e. detritus. Clay that is present is extremely silty and slightly humic, containing very fine sand.

Sand in this lithofacies is slightly silty and slightly humic, and has a sand median of 218 µm and well sorted. The most important median classes are medium coarse (26 %) and medium fine (23 %).

The most important sand median classes in the fine sand category are extremely fine (34%) and very fine (28%) and to a lesser extent, medium fine (20%). The medium category consists of medium coarse (28%) and medium fine (27%) sand. The coarse category has a sand median of 368 µm, with extremely coarse (37%) and very coarse (29%) as the most important sand medians.

Table A.8 Results of grain size analysis on the Boxtel Formation (undifferentiated), fluvial channel deposits. Compositional percentages and sand characteristics (sand median and uniformity coefficient) are median values (D50-percentile) of the sample data, shown only if 5 or more analyses have been performed.

Lithology or	Analysis (n)		Median (%)				Sand Median	
Sand cat.	Grain size	Org. comp.	Clay	Silt	Sand	Organics	D50 (µm)	CU
Sand	110	98	0.18	1.75	98.07	0.36	217.68	1.96
sand fine	9	9	1.35	15.39	81.79	0.71	133.52	1.75
sand medium	72	64	0.49	2.74	96.62	0.36	203.94	1.97
sand coarse	29	25	0.00	0.09	99.91	0.24	367.8	1.94

A.2.15 Boxtel Formation – bank and crevasse deposits

Deposits from this lithofacies have been encountered in 7 borings in the TopIntegraal study, with a total length of 21 meters. In the 16 meters of material that was described, 74 intervals have been identified. The fluvial bank and crevasse deposits almost exclusively occur in the Hunzedal, and are usually less than 3 m thick.

A.2.16 Core descriptions

Sediments consist of slightly silty non-calcareous sands, with a sand fraction of 98% and a median of 185 µm. Spread varies from moderately small to very large. Sand falls within the categories fine (median of 123 µm) and medium sand (194 µm). There is no clay fraction present in the sand. Traces of mica have been observed in 45% of the fine sand intervals, and in 30% traces of glauconite are present. Within the sand intervals as a whole, 15% contains detritus and over 20% contain loam beds.

A.2.17 Grain size analysis

Grain size analyses show that levee and crevasse deposits consists almost completely of sand – a single clay sample has been analysed. The clay is very sandy and moderately humic, containing medium fine sand.

Sand samples are slightly sandy and slightly humic, with a medium coarse grain size (median of 212 µm) and a well sorted (Table A.9). The most important sand median classes are medium coarse and medium fine sand (28% and 26%, respectively). Sand in the fine category is very silty and slightly humic with a very fine sand median (121 µm) and is very well sorted. Most grains belong to the median classes extremely fine (37%) and very fine (29%). The medium category is slightly silty and slightly humic, has a sand median of 215 µm and is well sorted. The most important sand medium classes are medium coarse (30%) and medium fine (29%). The coarse category is slightly silty, slightly humic and extremely coarse sand.

Table A.9. Results of grain size analysis on the Boxtel Formation (undifferentiated), bank and crevasse deposits. Compositional percentages and sand characteristics (sand median and uniformity coefficient) are median values (D50-percentile) of the sample data, shown only if 5 or more analyses have been performed.

Lithology or	Analysis (n)		Median (%)				Sand Median	
Sand cat.	Grain size	Org. comp.	Clay	Silt	Sand	Organics	D50 (µm)	CU
Sand	33	30	0.00	2.53	97.46	0.34	212.11	1.86
sand fine	5	5	1.03	19.43	79.54	0.70	120.73	1.69
sand medium	24	21	0.00	2.32	97.68	0.33	215.26	1.86

A.2.18 Boxtel Formation, Tilligte Member – bedded lake and abandoned channel deposits

The bedded lake and abandoned channel deposits in the Tilligte Mb. have been encountered in 21 cores.

A.2.19 Core descriptions

The core descriptions on this lithofacies can be grouped into different regions in which this lithofacies occurs, as characteristics regionally vary. The following description solely includes cores that were taken in the Hunze valley.

The sediment deposited in the Hunze valley is estimated to consist of 63% sand, 18% loam, 15% clay and 3% peat. The sand fraction of the sand is approximately 93% with a median of 132 µm, while silt (6%), clay (1%) and organic compounds (6%) are also present.

All sand categories are represented in this lithofacies: fine sand (median 101 µm) occurs in over 50% of all layers, while medium (176 µm) and coarse sand (400 µm) are present in respectively 44% and 6% of all layers. In all cores the sand layers are non-calcareous, except in three cores in the north of the Hunzedal. The calcareous sediments in these cores lie directly on top of the marine Eem Formation and contain traces of glauconite.
Composition of the loam layers is estimated at 6% clay, 70% silt, 24% sand and 9% organic components. For clay layers, composition is estimated at 28% clay, 62% silt, 9% sand and 6% organic components. Loams and clays have an olive grey or brown grey colour. Small amounts or traces of mica are found in 60% of all clay and loam layers.

A.2.20 Grain size analysis

Grain size analyses (Table A.10) on the bedded lake and abandoned channel deposits show an exceptionally heterogeneous unit. Samples vary from very clean sand to slightly silty clay. Peat is classified as either mineral-poor or very clayey. Sand admixed in the peat is medium fine.
Clay is extremely silty and slightly humic, but its composition varies from slightly to very sandy and slightly to extremely silty. The admixed sand is mainly composed of extremely fine sand (40%), with decreasing importance of coarser sand median classes from very fine sand (18%) to medium coarse sand (11%).
Loam is very sandy and slightly humic. The admixed sand is mainly composed of the very fine sand median class (58%), with decreasing amounts from the very fine (19%) to medium coarse (16%) classes.
Sand in this lithofacies is slightly silty and slightly humic, medium fine (median of 189 µm) and has a small spread. It mostly consists of medium fine and medium coarse sand median classes (each 25%) and to a lesser extent, very fine sand (18%). All three sand categories are represented. Most fine sand falls within the median classes extremely fine (38%) and very fine (34%) sand, both of which are well sorted. In the medium category, sand belongs to the medium fine and medium coarse sand (each 27%). Sand of the coarse category consists mostly of coarse sand (44%) but also contains very coarse (21%) and medium coarse (17%) sand. The coarse sand is poorly sorted.

Table A.10. Results of grain size analysis on the Tilligte Member (Boxtel Formation), bedded lake and abandoned channel deposits. Compositional percentages and sand characteristics (sand median and uniformity coefficient) are median values (D50-percentile) of the sample data, shown only if 5 or more analyses have been performed.

Lithology or Sand cat.	Analysis (n)		Median (%)				Sand Median	
	Grain size	Org. comp.	Clay	Silt	Sand	Organics	D50 (µm)	CU
Clay	44	43	16.64	46.31	39.39	3.78	120.33	1.88
Loam	30	30	10.89	59.58	27.59	4.11	96.56	1.57
Sand	62	60	1.29	6.51	92.58	0.65	189.00	2
sand fine	13	13	3.94	13.51	84.59	2.18	121.41	1.71
sand medium	43	42	1.18	5.04	93.84	0.46	195.02	2.05
sand coarse	6	5	0.51	2.20	97.29	0.73	384.4	2.51

A.2.21 Boxtel Formation – slope deposits

Slope deposits are a relatively thin unit that has been encountered in 12 cores within the TopIntegraal study, adding up to a cumulative thickness of 9.3 meters. Fifty intervals have been identified in 8 meters of sediment that was described in more detail.

A.2.22 Core descriptions

Sand in 35 of the described intervals is non-calcareous, with a sand fraction of 93% and a sand median of 183 µm. The fine and medium sand categories have a sand median of respectively 121 µm and 199 µm. Sediment colour ranges from grey to yellowish brown. Glauconite and mica occur in two of the distinguished intervals. Loam beds occur in 20% of the sand layers. Loam intervals (9) are non-calcareous, contain on average 21% silt and 2% gravel, and are mostly greenish grey. The loam has a firm consistency.

A.2.23 Grain size analysis

Clay in this lithofacies is very sandy and slightly humic. The sand fraction (60%) is medium coarse.

Sand samples in this lithofacies are slightly silty and slightly humic. The sand is medium coarse (sand median of 238 µm) and poorly sorted (Table A.11). The most important sand median class is medium coarse (28%), but very coarse (19%) and medium fine (18%) sand is also present. The important median classes in the medium category are medium coarse (31%) and medium fine (25%) sand. The coarse category consists mostly of sand in the very coarse median class.

Table A.11. Results of grain size analysis on the Boxtel Formation (undifferentiated), slope deposits. Compositional percentages and sand characteristics (sand median and uniformity coefficient) are median values (D50-percentile) of the sample data, shown only if 5 or more analyses have been performed.

Lithology or	Analysis (n)		Median (%)				Sand Median	
Sand cat.	Grain size	Org. comp.	Clay	Silt	Sand	Organics	D50 (µm)	CU
Sand	13	11	1.32	2.81	96.05	0.36	237.6	1.91
sand medium	8	7	1.18	3.01	95.71	0.36	231.8	2.3

A.3 Eem Formation

A.3.1 Genesis

During the last glaciation, ice movement in a north-north-west to south-south-east direction has eroded a multiple kilometers wide and tens of meters deep depression into the Northern Netherlands Plateau; the Hunze valley. During the melt of the ice sheet and following period, the remaining valley was partially filled with glacial and periglacial deposits. As a result of sea-level rise, the sea inundated the land and a large tidal area developed.

A.3.2 Members and Beds

Within the Eem Formation, additional Members and Bedss have not been distinguished. An overview of grain size analysis for all samples taken within the Eem Formation, without dividing them into their separate lithofacies, can be found in Table A12.

A.3.3 Extent

Marine sediments of the Eem Formation were deposited in the low-lying areas, that is, the coastal region and former valleys in the northern Netherlands. The main facies are tidal channel deposits, with a base at approximately 2 to 48 meters below NAP and a maximum thickness of 32 meters. Tidal flat and lagoonal deposits also formed. Along the coast of the Wadden Sea, the Eem Formation can have a thickness of up to 10 meters, with its base lying at 12 to 15 m below NAP (Figure A.4).

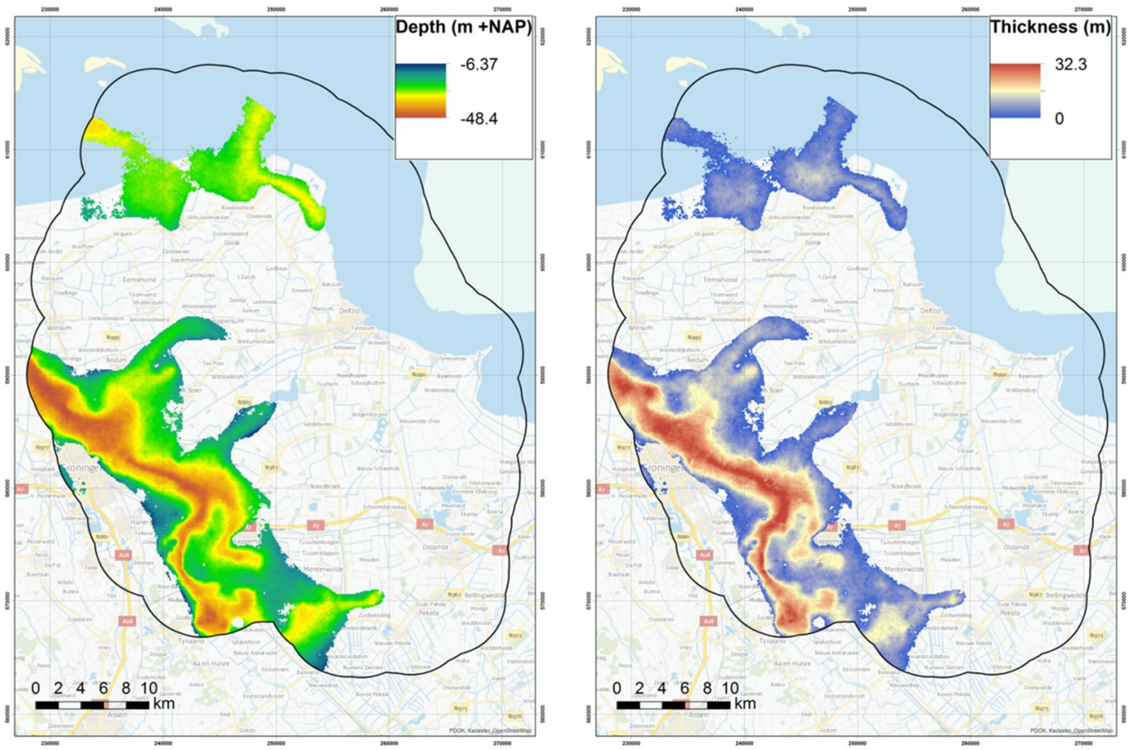

Figure A.4. Depth of the base (left) and thickness (right) of the Eem Formation GeoTOP model unit (Maljers, et al., 2016) in the Groningen gas field + 5km buffer.

A.3.4 Lithology

Lithology of different lithofacies is described separately in the following paragraphs. An overview of results of grain size analysis for all lithofacies combined can be found in Table A12.

Table A.12. Results of all grain size analyses on the Eem Formation. Compositional percentages and sand characteristics (sand median and uniformity coefficient) are median values (D50-percentile) of the sample data, shown only if 5 or more analyses have been performed.

Lithology or	Analysis (n)		Median (%)				Sand Median	
Sand cat.	Grain size	Org. comp.	Clay	Silt	Sand	Organics	D50 (µm)	CU
Clay	32	31	20.32	49.89	27.63	3.21	94.19	1.49
Loam	12	12	15.9	62.33	22.09	3.29	90.63	1.46
Sand	50	46	1.4	5.48	92.46	0.62	159.55	1.81
sand fine	22	21	1.31	9.71	89	0.55	111.98	1.59
sand medium	18	16	1.4	3.31	94.85	0.67	183.91	1.92
sand coarse	10	9	0.96	2.83	96.21	0.66	395.88	2.23

A.3.5 Lithofacies

Lithofacies that have been distinguished in the Eem Formation are:

- Tidal channel deposits (fine, medium and coarse sand, clay)
- Tidal flat deposits (fine sand, clay, loam)
- *Lagoonal deposits (clay)*

Lithofacies printed in *italic* are not discussed in this report, due to their low sand content.

A.3.6 Eem Formation – tidal channel deposits

The tidal channel facies of the Eem Formation have been distinguished in 10 out of 75 TopIntegraal cores, covering a total of 39 meters. Within the lithofacies, 32 meters are described, and 100 intervals have been identified.

A.3.7 Core descriptions

The tidal channel deposits in the Eem Formation consist of thick sequences of calcareous sand, although clay and loam intervals make up approximately 35% of the lithofacies.
The slightly silty sands have a sand fraction of 97% (median 196 µm). In general, the sands are calcareous and contain traces of gravel and organic material. Approximately 53% of all layers consist of sand that falls within the fine sand category (median of 123 µm and a moderately small spread), 33% falls within the medium category (median 203 µm) and 14% within the coarse category (median 400 µm, with a very large spread). Sand within the medium and coarse category contains shells of shell fragments – usually less than 5%. Small amounts or traces of mica have been found in half of all intervals, and small amounts or traces of glauconite have been found in a third of all intervals. The layers are greenish, olive or brownish grey. Of all sand intervals, 30% has internal bedding due to sedimentary structures. Thin beds of detritus and clay occur in half of the sand intervals, and sublayers (more clay than detritus) are present in a third of all sand intervals.

A.3.8 Grain size analysis

Results on the grain size analyses can be found in Table A.13. Clay in this lithofacies is extremely silty and medium humic, but varies from medium to very sandy and very to extremely silty. The admixed sand within clay samples is very fine (median of 111 µm) and is

well sorted; it is mainly composed of the extremely fine sand median class (44%). Loam samples are very sandy and medium humic, containing admixed sand that is mostly extremely fine, although extremely coarse sand is also present.
Sand is slightly silty, slightly humic, moderately fine with a median of 184 µm and is well sorted. All sand median classes occur, with very fine (21%), medium fine (18%) sand being the most important ones. Fractions of the other classes vary between 10 and 14%.
The most important median class in the fine sand category is very fine sand (40%) followed by extremely fine sand (34%). For the medium category, the most important median classes are medium fine sand (28%), followed by medium coarse (24%) and very fine (20%) sand. The coarse category consists of extremely coarse (44%) and very coarse (26%) sand. The sorting varies from very well sorted (fine sand) to poorly sorted (coarse sand)

Table A.13. Results of grain size analysis on the Eem Formation, tidal channel deposits. Compositional percentages and sand characteristics (sand median and uniformity coefficient) are median values (D50-percentile) of the sample data, shown only if 5 or more analyses have been performed.

Lithology or	Analysis (n)		Median (%)				Sand Median	
Sand cat.	Grain size	Org. comp.	Clay	Silt	Sand	Organics	D50 (µm)	CU
Clay	13	13	16.19	48.84	32.78	4.08	110.96	1.61
Sand	38	35	1.40	3.61	94.66	0.66	183.91	1.87
sand fine	11	11	1.22	4.89	94.32	0.52	117.87	1.60
sand medium	17	15	1.42	3.17	95.45	0.67	184.18	1.88
sand coarse	10	9	0.96	2.83	96.21	0.66	395.88	2.23

A.3.9 Eem Formation – tidal flat deposits

Tidal flat deposits within the Eem Formation have been encountered in 7 of 75 TopIntegraal cores. Layers mostly consist of clay and sand, with a small amount of loam layers. These tidal flat deposits have not been recoved in boreholes in the study area of the Groningen gas field. However, it can be expected that they are present in the study area.

The tidal flat deposits consist for 60% out of sand and 40% out of clay layers (Table A.14). The weakly to moderately silty sand consist for 90% of sand (sand median 110 µm) and are very well sorted. 80& of the sand layers contains some mica, The sands are olive grey and contain 24% lutum and 5% organic material.
Only 10% of the sand layers and half of the clay layers shows sedimentary structures. However, 60% of the sands contains thin clay beds and 40% of the clay contains thin sand beds.

Grain size analysis

A total of 34 sampes have been analysed, of which 16 samples were clay, 6 samples loam and 12 samples sand. The sand is medium silty and weakly humic. It is very fine (sand median 109 µm) and very well sorted. It mainly consists out of extremely fine (45%) and very fine (35%) grains.

Table A.14. Results of grain size analysis on the Eem Formation, tidal flat deposits. Compositional percentages and sand characteristics (sand median and uniformity coefficient) are median values (D50-percentile) of the sample data, shown only if 5 or more analyses have been performed.

Lithology or Sand cat.	Analysis (n)		Median (%)				Sand Median	
	Grain size	Org. comp.	Clay	Silt	Sand	Organics	D50 (µm)	CU
Clay	16	15	18.59	52.26	27.63	2.31	90.96	1.48
Loam	6	6	17.57	64.79	17.64	2.98	85.61	1.4
Sand	12	11	1.38	9.71	89.00	0.55	108.99	1.53
sand fine	11	10	1.41	10.43	88.57	0.61	108.8	1.53

A.4 Drente Formation

A.4.1 Genesis

The Drente Formation within the study area consists of sediments that were formed by or near to the Saalian ice sheet (Saalian: 238 - 126 ka). Vast areas of glacial till or ground moraines were formed as the Saalian ice sheet expanded over the Northern part of the Netherlands. Fluvioglacial sediments have been deposited in the form of sandurs and kame terraces, and partially on and under the ice as eskers and kame structures. Morphologically, sandurs are related to the low-lying areas of meltwater breakthroughs of ‘pushed’ moraines. Kame terraces have usually formed along the flanks of the pushed moraines. Outside the study area, basin fills and lacustrine sediments are deposited in proglacial lakes. Sediments have been deposited in the Middle and Late Saalian.

A.4.2 Members and Beds

The Drente Formation within the study area is subdivided into two members: the Gieten Member and the Schaarsbergen Member. The Gieten Member consists of glacial tills, whereas the Schaarsbergen Member is made up of fluvioglacial deposits. The Uitdam Member, including the Oosterdok Bed, only occurs in the large glacial basins in the central part of the Netherlands.

The Schaarsbergen deposits are mainly found in the Hunze Valley, where de Gieten Member is absent. The glacial tills of the Gieten Member are found on the Drenthe till plateau and east of the Hunze Valley, but are usually absent in brook valleys.

A.4.3 Extent

Sediments of the Drente Formation as a whole occur in about 70% of the cores that were taken within the TopIntegraal Study. The cumulative thickness of the Formation is 213 meters. In 19 cores, the formation was absent, and in the remaining cores the formation may be present but has not been reached.

The extent of the Schaarsbergen Member according to is shown in Figure A.5.

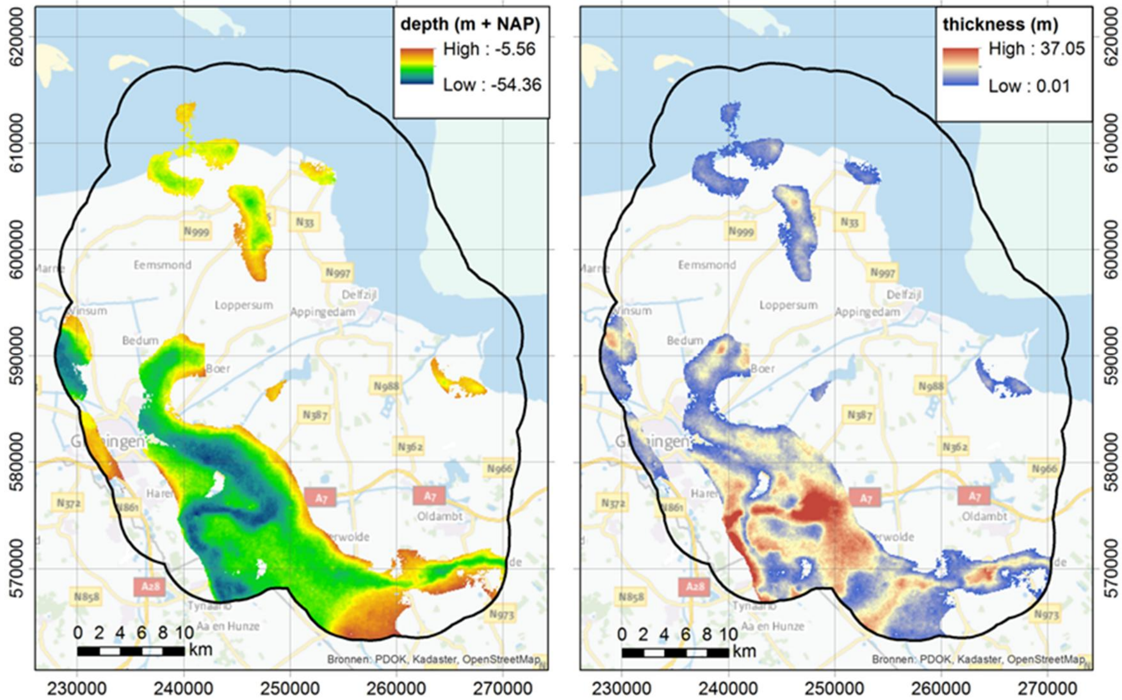

Figure A.5. Depth of the base (left) and thickness (right) of the Drente GeoTOP model unit (Maljers, et al., 2016) in the Groningen gas field + 5km buffer. The Gieten model unit is modelled as a separate unit and not incorporated in this picture.

A.4.4 Lithology

Grain size analysis for the Gieten Member and Schaarsbergen Member combined are not readily available, and not relevant to this study.

A.4.5 Lithofacies

Lithofacies that have been distinguished in the Drente Formation are:

- *Subglacial massive diamict (clay, loam, fine and medium sand; glacial till)*
- *Subglacial bedded diamict (medium sand; bedded glacial till)*
- Pradolina deposits (fine, medium and coarse sand)

Lithofacies printed in *italic* are not discussed in this report. The glacial tills of the Gieten Member are considered not to be susceptible to liquefaction.

A.4.6 Drente Formation – Schaarsbergen Member – pradolina deposits

The majority of the 10 cores in which the pradolina deposits of the Schaarsbergen Member have been described, are located in the Hunze valley. The lithofacies is considered to be highly uniform, consisting almost entirely of sand.

A.4.7 Core descriptions

The slightly silty sand has an estimated sand fraction of 98%, with a sand median of 195 µm and an average gravel content of 2% (Table A.15). In the coarse category, gravel content can be as high as 7%. Sorting in grain size varies from well to very poorly sorted. Sand medians for the fine, medium and coarse categories are 130 µm, 201 µm and 366 µm, respectively.

Most of the sand within this lithofacies falls within the medium sand category. However, fine (30%) and coarse (10%) sands do also occur. Several thin layers of gravel and 10 to 20 centimeter thick layers of clay and loam have been observed in the sediment.
Two thirds of the described intervals is calcareous, and 20% contains at least traces of mica. Half of the intervals show traces of glauconite. The sediment has a grey to olive grey colour. In about half of the intervals, sedimentary structures show internal bedding. Intercalation with different lithologies occurs in 15% of all sand intervals. The sublayers include clay and loam beds.

A.4.8 Grain size analysis

Samples classified as clay are not proper clays; 4 out of 5 samples are derived from coarse sand layers that contain beds built up of clay blocks. The fifth originates from a core near Schoonenbeek, where loamy intervals with properties resembling glacial till are intercalated in the Schaarsbergen Member. The analysed clay samples are slightly sandy and slightly humic, with a high sand and low silt content. The admixed sand has a sand median of 212 µm and is poorly sorted. The uniformity coefficient of the grain size spectrum from 0 to 2000 µm is very large (24.4), almost identical to that of the Gieten Mb. glacial till. This is in agreement with the genesis of the Schaarsbergen Member, which partly consists of eroded and redeposited local sediments, such as the glacial till of the Gieten Member.
Fluvioglacial sand is slightly silty and slightly humic. It is medium coarse, with a sand median of 289 µm. The most important sand median classes are medium coarse sand (24%) and very coarse sand (22%), which are well sorted. In most cases, sand falls within the medium and coarse sand categories, with a respective sand median of 245 µm and 396 µm. The medium category consists of medium coarse (34%), medium fine and very coarse sand (each 21%). The coarse category consists of extremely coarse sand (44%) and very coarse sand (24%).

Table A.15. Results of grain size analysis on the Drente Formation - Schaarsbergen Member, pradolina deposits. Compositional percentages and sand characteristics (sand median and uniformity coefficient) are median values (D50-percentile) of the sample data, shown only if 5 or more analyses have been performed.

Lithology or	Analysis (n)		Median (%)				Sand Median	
Sand cat.	Grain size	Org. comp.	Clay	Silt	Sand	Organics	D50 (µm)	CU
Clay	5	5	13.18	23.02	61.45	1.39	212.28	2.32
Sand	57	55	0	0.83	99.17	0.36	288.68	1.98
sand medium	31	30	0	1.26	98.53	0.34	244.85	1.83
sand coarse	24	23	0	0.09	99.91	0.4	395.88	2.25

A.5 Urk Formation, Tynje Member

A.5.1 Genesis

The Urk Formation, Tynje Member consists mostly of fluvial Rhine deposits. After the disappearance of the Elsterien ice sheet, the river Rhine ran in north-west direction, through the proto-Rhine valley in Friesland. The Urk Formation is made up of fluvial Rhine deposits. In the northern Netherlands sediments deposited in a fresh water tidal environment, or near-coastal marine environment, also are part of the Urk Formation. Due to the pressure of the Saalian ice sheet, the marine clays have compacted. Sediments of the Urk Formation have been deposited from the end of the Cromerian until the Mid-Saalian.

A.5.2 Members and Bedss

The Urk Formation is subdivided into the Veenhuizen Member (stratigraphically positioned below the Peelo Formation) and the Tynje Member (superposing the Peelo Formation). In near-coastal areas, coarse sands containing gravel that have been assigned to the Urk Formation (Tynje Member) may not belong to the Urk Formation. The recent discovery of glacial tills belonging to the Peelo Formation implies that these coarse sands were formed during the Elsterien and should be considered as part of the Peelo Formation. However, reworking of the Peelo sediments and deposition in a later stage cannot be ruled out.

A.5.3 Extent

The Tynje Member is locally present in the study area (Figure A.6). The base of the member is about 30m and it can reach 15 m thickness.

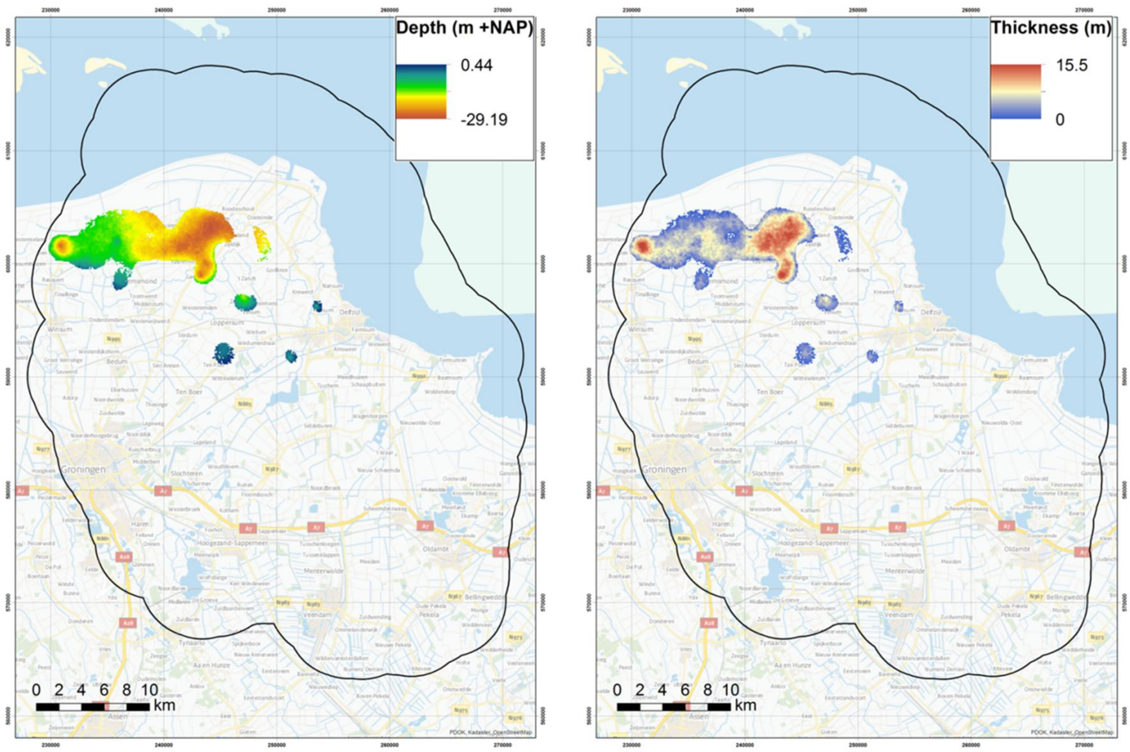

Figure A.6. Depth of the base (left) and thickness (right) of the Urk Formation, Tynje Member GeoTOP model unit (Maljers, et al., 2016) in the Groningen gas field + 5km buffer.

A.5.4 Lithology

An overview of results of grain size analysis for all lithofacies combined can be found in Table A.. Lithology of different lithofacies is described separately in the following paragraphs.

Table A.16. Results of grain size analyses on the Urk Formation - Tynje Member. Compositional percentages and sand characteristics (sand median and uniformity coefficient) are median values (D50-percentile) of the sample data, shown only if 5 or more analyses have been performed.

Lithology or	Analysis (n)		Median (%)				Sand Median (µm)	
Sand cat.	Grain size	Org. comp.	Lutum	Silt	Sand	Organics	D50	CU
Peat	11	17	3.26	17.39	14.11	52.7	125.32	2.07
Clay	73	70	20.18	52.5	23.76	2.63	104.09	1.7
Loam	26	24	18.19	67.08	17.29	3.06	87.69	1.43
Sand	229	200	0	0.85	98.91	0.37	272.93	1.85
sand fine	28	27	2.29	11.75	85.01	0.52	125.96	1.64
sand medium	99	87	0.34	1.93	97.89	0.38	225.06	1.86
sand coarse	102	86	0	0.04	99.96	0.32	432.68	1.95

A.5.5 Lithofacies

Lithofacies that have been distinguished in the Urk Formation, Tynje Member are:

- Coarse channel deposits (coarse sand and gravel)
- Channel deposits (fine to coarse sand)
- Levee and crevasse deposits (medium and coarse sand)
- *Bedded lake and abandoned channel deposits (clay, loam, peat, gyttja)*
- Tidal channel deposits (medium sand)
- Tidal flat deposits (fine sand, clay, loam)
- *Lagoonal deposits (clay, loam)*
- *Swamp deposits (peat, clay, sand)*

Lithofacies printed in *italic* are not discussed in this report, due to their low sand content.

A.5.6 Urk Formation, Tynje Member – Coarse channel, channel and levee and crevasse deposits

The three sandy fluvial lithofacies are combined in the description of the core descriptions. Channel deposits are the most common deposit in the Tynje Member, before Coarse channel deposits and levee and crevasse deposits.

A.5.7 Core descriptions

Ten gravel beds have been described within this unit, with an average gravel fraction of 57%. Fluvial sands found are non-calcareous, with an average sand fraction of 98%, 2% silt, no clay fraction, and 2% organic material. The coarse channel deposits have on average 2% gravel. The three lithofacies coarse channel, channel and crevasse and levee lithofacies have different median values for their sand medians; 553 µm, 173 µm and 236 µm respectively.
In over 50% of the fine sand intervals, small amounts or traces of mica are present, especially in the channel and levee and crevasse lithofacies. Glauconite occurs in 60% of the sandintervals of the channel deposits, and to a lesser degree it also occurs in both channel deposits.
Sands from the fine sand category have an average estimated sand percentage of 95%, containing approximately 4% silt and 3% organic material. Sand medians for the fine, middle and coarse category are respectively 130 µm, 220 µm and 480 µm.

Internal bedding within the sand intervals occurs mainly in the channel deposits and levee and crevasse deposits, where over half of the intervals is bedded. South-west of the study area of Groningen, thin clay and peat layers have been found within the Tynje Member, but this has not been observed in other TOPINTEGRAAL cores in the northern Netherlands.

A.5.8 Grain size analysis – coarse channel deposits

Result of grain size analysis on the coarse channel deposits can be found in Table A.. Two clay samples that were analysed show that clay within this unit is extremely silty and medium humic. Sand admixed in the clay samples is very fine.
Sand in this lithofacies has a sand fraction of almost 100% with almost no admixed fines; it has a sand median of 570 µm and is well sorted. The most important sand median class is extremely coarse (76%) and the sand is well sorted.

Table A.17. Results of grain size analyses on the Urk Formation - Tynje Member, coarse channel deposits. Compositional percentages and sand characteristics (sand median and uniformity coefficient) are median values (D50-percentile) of the sample data, shown only if 5 or more analyses have been performed.

Lithology or	Analysis (n)		Median (%)				Sand Median	
Sand cat.	Grain size	Org. comp.	Clay	Silt	Sand	Organics	D50 (µm)	CU
Sand	49	39	0	0.08	99.92	0.4	570.04	1.98
sand coarse	48	38	0	0.08	99.92	0.4	570.41	1.99

A.5.9 Grain size analysis – channel deposits

Analyses on four clay samples shows that clay within this lithofacies is extremely silty and medium humic, which contains mainly very fine admixed sand.
Sand samples (Table A.18) are slightly silty and slightly humic, with a sand median of 260 µm and is well sorted. The sand median varies strongly around the median value: medians fall between 105 and 469 µm, the D5 and D95-percentiles. The sand median classes medium coarse (24%) and very coarse (21%) are most common, but other classes also have a significant contribution.
All three sand categories are present in the samples. The fine category is medium silty and slightly humic with a relatively high contribution of clay and silt. The most common sand median classes are very fine (32%) and extremely fine (30%), although there are large differences between samples. The medium and coarse category are slightly silty and slightly humic. The medium category is medium coarse with the highest contribution of the medium coarse (29%) and medium fine (24%) sand median classes. The coarse category is very coarse with extremely coarse (41%) and very coarse (30%) being the dominating sandmedian classes. The fine sand class is very well sorted, the other classes are well sorted.

Table A.18. Results of grain size analyses on the Urk Formation - Tynje Member, channel deposits. Compositional percentages and sand characteristics (sand median and uniformity coefficient) are median values (D50-percentile) of the sample data, shown only if 5 or more analyses have been performed.

Lithology or	Analysis (n)		Median (%)				Sand Median	
Sand cat.	Grain size	Org. comp.	Clay	Silt	Sand	Organics	D50 (µm)	CU
Sand	107	103	0.03	1.12	98.63	0.35	259.58	1.86
sand fine	15	15	2.29	13.68	83.33	0.52	124.36	1.68
sand medium	53	52	0.34	1.75	98.11	0.36	227.74	1.96
sand coarse	39	36	0	0.01	99.99	0.29	388.87	1.88

A.5.10 Grain size analysis – levee and crevasse deposits

Results of the grain size analyses can be found in Table A.19. The levee and crevasse deposits are nearly completely composed of sand; one peat sample was analysed (44% organic matter content) but the grain size analysis failed. Sand is slightly silty and slightly humic and with a sand median of 244 µm, it is classified as medium coarse and is very well sorted. It is exceptionally clean with a sand fraction over 99%. Sand within this lithofacies is mainly composed of the sand median classes medium coarse (26%), medium fine (11%) and very coarse (21%). All three sand categories occur, and are slightly silty and slightly humic. The fine category consist mostly of very fine sand, whereas the medium category is medium coarse (median of 229 µm) and mostly built up of sand median classes medium coarse (33%) and medium fine (24%). The coarse category is very coarse (median of 348 µm) with very coarse (35%) and extremely coarse (32%) as its most important sand median classes.

Table A.19. Results of grain size analyses on the Urk Formation - Tynje Member, levee and crevasse deposits. Compositional percentages and sand characteristics (sand median and uniformity coefficient) are median values (D50-percentile) of the sample data, shown only if 5 or more analyses have been performed.

Lithology or	Analysis (n)		Median (%)				Sand Median	
Sand cat.	Grain size	Org. comp.	Clay	Silt	Sand	Organics	D50 (µm)	CU
Sand	32	21	0.00	0.41	99.59	0.36	243.66	1.77
sand medium	23	15	0.00	0.85	99.15	0.32	228.77	1.77
sand coarse	7	4	0.00	0.00	100.00	-	348.21	1.80

A.5.11 Urk Formation, Tynje Member – tidal channel

In the TopIntegraal study, the tidal channel lithofacies has only been observed in 3 out of 75 cores that were taken. The unit consists for approximately 90% of sand and 10% clay intervals. Although this facies has not been found in TOPINTEGRAAL cores within the Groningen study area, it shall shortly be described because of its high sand content and possible (local) occurrences in the study area.

A.5.12 Core description

The majority of sediments within this lithofacies consists of calcareous sands with a sand fraction of 97%, 3% silt and 2% organic material. It has a sand median of 195 µm. Most sands belong to the fine and medium category (sand median of 121 µm and 183 µm, respectively) with a sand fraction of 95 to 99% and traces of glauconite. Sediments are grey to greenish grey, and almost two thirds of the layers are bedded. No sublayers have been described.

A.5.13 Grain size analysis

Four clay samples that were analysed show that clay within this lithofacies is very sandy (58%) and slightly humic; the admixed sand is very fine.

Grain size analyses on samples of sand (results shown in Table A.) show that sand is slightly silty and slighty humic; some samples are medium to very silty. The most important median classes are medium coarse (29%) and medium fine sand (26%).

Samples belong to all three sand categories, although fine sand is rare. The fine category is very silty and slightly humic and classified as very fine. Sand from the middle and coarse categories is slightly silty and slightly humic. The coarse category is the cleanest, with a sand fraction of nearly 100% and a very coarse sand median (336 µm) and is well sorted. It contains sand from the extremely coarse and very coarse sand median classes (each 34%). Sand of the medium category is medium coarse (median 210 µm) with medium coarse (39%)

and medium fine (33%) being the most important sand median classes. This category is very well sorted.

Table A.20. Results of grain size analyses on the Urk Formation - Tynje Member, tidal channel deposits. Compositional percentages and sand characteristics (sand median and uniformity coefficient) are median values (D50-percentile) of the sample data, shown only if 5 or more analyses have been performed.

Lithology or	Analysis (n)		Median (%)				Sand Median	
Sand cat.	Grain size	Org. comp.	Clay	Silt	Sand	Organics	D50 (µm)	CU (D60/D10)
Sand	19	16	0.80	3.02	96.04	0.34	224.13	1.76
sand medium	10	7	1.02	3.49	95.56	0.67	209.98	1.75
Sand coarse	7	7	0.00	0.09	99.90	0.24	336.20	1.91

A.5.14 Urk Formation, Tynje Member – tidal flat

The tidal flat lithofacies has been encountered in 7 out of 75 TopIntegraal cores. The layers mainly consist of (fine) sand and clay.

A.5.15 Core descriptions

Sand intervals in this unit are very fine (median of 121 µm) and contain on average 1% of clay, 6% silt and 94% sand; some intervals are extremely fine. Approximately half of the intervals is calcareous, and in one of the cores shell remains have been found. Traces or higher quantities of glauconite have been found in 80% of the sand intervals; the colour of the sand is a greenish grey.
The clay intervals, as well as several loam intervals, contain on average 28% clay, 62% silt, 10% sand and 4% organic material. The majority is calcareous and mica is present in 80% of all clay intervals, which have a grey to greenish grey colour and are moderately firm to firm.

A.5.16 Grain size analysis

The tidal flat lithofacies is a very heterogeneous unit that consists of clay, loam and sand, as can be seen in Table A.. Clays vary from medium to very sandy and very to extremely sitly and are slightly humic. The admixed sand is extremely fine, dominated by grains from the extremely fine sand median class (71%).
Loam samples are very sandy and slightly humic, containing admixed sand that mainly belongs to the extremely fine sand median class (74%).
The sand samples are slightly silty and slightly humic, although some samples are moderately to extremely silty. The most important sand median classes are medium fine (34%) and very fine (30%) sand. Sand of the fine category is slightly silty an slightly humic, and with a sand median of 122 µm it is very fine. The most important median classes are very fine (36%) and extremely fine (35%). Sand from the medium category is slightly silty and slightly humic; it is medium coarse with the most important sand median classes medium fine (38%), very fine (25%) and medium coarse (23%).

Table A.21. Results of grain size analyses on the Urk Formation - Tynje Member, tidal flat deposits. Compositional percentages and sand characteristics (sand median and uniformity coefficient) are median values (D50-percentile) of the sample data, shown only if 5 or more analyses have been performed.

Lithology or	Analysis (n)		Median (%)				Sand Median	
Sand cat.	Grain size	Org. comp.	Clay	Silt	Sand	Organics	D50 (µm)	CU
Clay	13	13	15.15	47.09	38.08	1.72	87.97	1.43
Loam	6	6	15.61	62.34	21.99	4.30	86.03	1.39

Sand	13	12	0.48	3.15	96.20	0.37	158.90	1.65
sand fine	6	5	0.95	10.10	89.10	0.40	121.96	1.59
sand medium	7	7	0.46	2.77	96.75	0.34	171.01	1.81

A.6 Peelo Formation

A.6.1 Genesis

In general, the Peelo Formation is presumed to be of glacial origin, although the almost complete absence of glacial till is remarkable. The environment in which the deposits were formed cannot be compared to that in which the Drente Formation developed; the formation of the Peelo sediments can only be explained by the presence of exceptional amounts of meltwater, leading to the deposition of very typical deposits including sequences of homogeneous sand that can be over 10 meters thick. Sediments of the Peelo Formation can be subdivided in a fine and a coarse facies. In both cases, deposition is attributed to meltwater pulses in the Elsterien ice age.

One of the characteristics of the Peelo Formation is its deeply incising valleys that can reach a depth of up to several hundreds of meters. These valleys have a strong variation in depth over relatively short distances, and are often interpreted as subglacial valleys that formed during meltwater pulses. Directly after their formation, they have been filled with their own erosive products and glaciolacustrine deposits, during and after retreat of the ice front.

A.6.2 Members and Beds

Within the Peelo Formation, the Nieuwolda Member is recognised. This member has a strong contrast to very sandy nature of the rest of the formation, as it composed of compact clays (pot clay) or alterations of compact clay and sand beds on a centimetre scale.

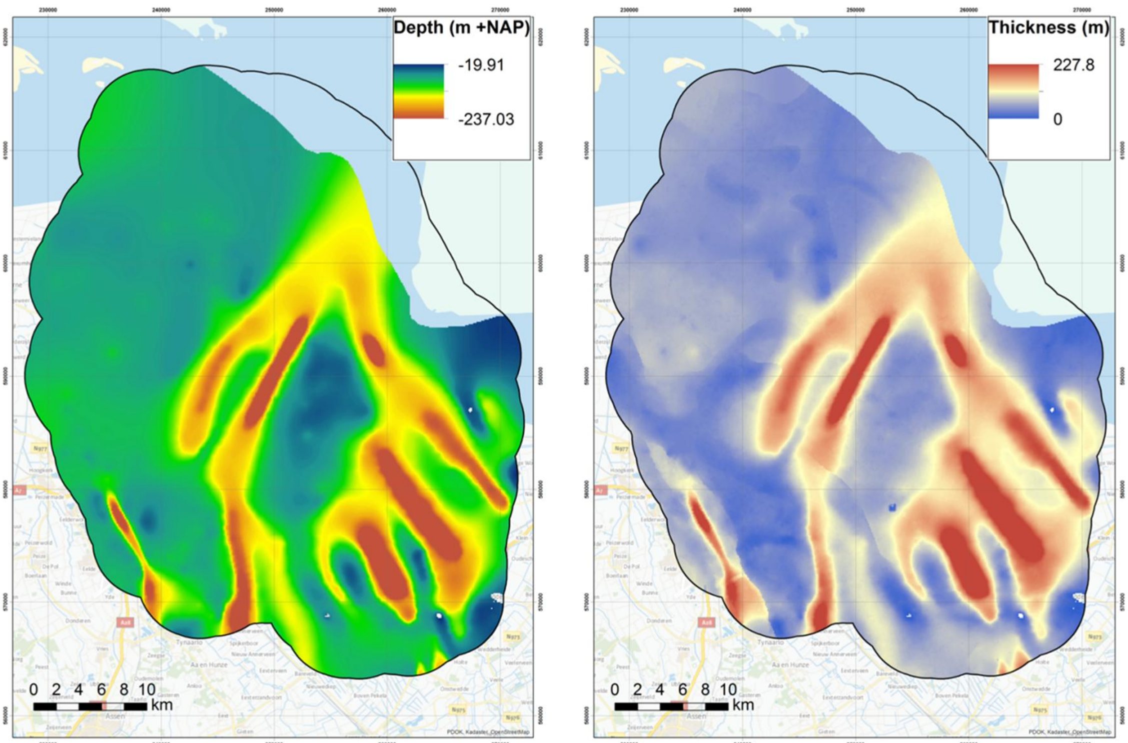

Figure A.7. Depth of the base (left) and thickness (right) of the Peelo GeoTOP model unit (Maljers, et al., 2016) in the Groningen gas field + 5km buffer.

A.6.3 Extent

Sediment of the Peelo Formation has been found in 24 out of 75 cores that were taken within the TopIntegraal study, and may be present at greater depth in 45 other cores; in six cores the Peelo Formation is absent. Cores that did not contain sediment of the Peelo Formation lie along the edge of the TopIntegraal study area and the Groningen gas field including a 5 km buffer. The Peelo Formation is present everywhere in the subsurface of our study area (Figure A.7).

Thickness and depth of the Peelo Formation can be highly variable over short distances. Within the deeply-incised glacial tunnel valleys, the sediment sequence can get several hundreds of meter thick, whereas outside of the valleys depths of 20 to 30 meters can be reached.

A.6.4 Lithology

The Peelo Formation has a remarkable lithology, with thick sequences of monotone very fine sand and compact clay-rich 'pottery clay'. Results of grain size analyses on all Peelo Formation samples are shown in Table A.. Most of the sand is fine grained, but coarser sands with sand medians varying from medium to extremely coarse also occur.

Based on their occurrence, a subdivision can be made into sands with a sand median smaller than 210 µm and a group with a larger sand median, 20% of which has intercalated sand beds with a smaller median. The first group encompasses the fine glacial outbreak deposits, and the second group comprises the coarse glacial outbreak deposits.

Table A.22 Results of grain size analyses on the Peelo Formation. Compositional percentages and sand characteristics (sand median and uniformity coefficient) are median values (D50-percentile) of the sample data, shown only if 5 or more analyses have been performed.

Lithology or Sand cat.	Analysis (n)		Median (%)				Sand Median (µm)	
	Grain size	Org. comp.	Lutum	Silt	Sand	Organics	D50	CU
Clay	8	8	10.87	36.84	52.59	1.88	117.55	1.77
Loam	10	10	9.57	54.35	35.29	0.86	88.19	1.47
Sand	285	277	0.53	3.27	96.14	0.47	160.87	1.7
sand fine	127	123	1.08	7.16	91.99	0.53	119.52	1.6
sand medium	103	103	0.46	2.48	97.02	0.46	202.02	1.83
sand coarse	55	51	0	0.17	99.83	0.32	468.58	2.52

A.6.5 Lithofacies

Lithofacies that have been distinguished in the Peelo Formation are:

- Glacial outbreak deposits, coarse facies (medium and coarse sand)
- Glacial outbreak deposits, fine facies (fine and medium sand, clay, loam)
- *Glaciolacustrine deposits (clay, loam, fine sand, 'potclay')*
- Subglacial massive diamict (medium sand; glacial till)

Lithofacies printed in *italic* are not discussed in this report, due to their low sand content.

A.6.6 Peelo Formation – coarse glacial outbreak deposits

The coarse facies of glacial outbreak deposits has been encountered in 7 out 75 cores within the TopIntegraal study.

A.6.7 Core descriptions

Sand fraction of the coarse glacial outbreak deposits is estimated at 98%, with 1% of gravel and 2% of organic material. The average sand median is 374 µm and the sands are very poorly sorted. Apart from the coarse sand, intercalating thick beds of fine non-calcareous sands have been observed.

Sand in the coarse category has a sand median of 560 µm, while for the medium category this is 214 µm. A third of the intervals contain traces of mica, although some contain larger amounts. Traces or small amounts of glauconite are present in 80% of all intervals. In 40% of all intervals, the sand is bedded, while in 4% of the intervals thin clay beds are present.. Sublayers have not been described in detail.

A.6.8 Grain size analysis

The coarse outbreak deposits have an average sand median of 359 µm and well sorted. They are mainly composed of the extremely coarse (35%), very coarse (21%) and medium coarse (17%) sand median classes (Table A.23). The contribution of the extremely coarse sand median class is exceptionally variable: values vary from 0.18% to 86% (D5 and D95-percentile).

Sand of the medium sand category is slightly silty and slightly humic and has a median of 230 µm. The most common sand median classes are medium coarse (31%) and medium fine (26%). Sand within the coarse category is slightly silty and slightly humic, but contains less clay, silt and organic material. Samples within this category are mainly composed of extremely coarse (63%) and very coarse (17%) sand, with a median of 512 µm. The medium sand is well sorted while the coarse sand is poorly sorted.

Table A.23 Results of grain size analyses on the Peelo Formation, coarse glacial outbreak deposits. Compositional percentages and sand characteristics (sand median and uniformity coefficient) are median values (D50-percentile) of the sample data, shown only if 5 or more analyses have been performed.

Lithology or	Analysis (n)		Median (%)				Sand Median	
Sand cat.	Grain size	Org. comp.	Clay	Silt	Sand	Organics	D50 (µm)	CU
Sand	81	77	0	0.57	99.39	0.47	359.21	2.16
sand medium	34	34	0.39	1.8	97.84	0.67	230.33	1.87
sand coarse	46	42	0	0.11	99.89	0.33	512.06	2.5

A.6.9 Peelo Formation – fine glacial outbreak deposits

Fine glacial outbreak deposits have been found in 19 out of 75 cores within the TopIntegraal study. The unit is mainly composed of sand, with some loam and clay.

A.6.10 Core descriptions

The fine glacial outbreak deposits of the Peelo Formation consist of extremely fine to very fine non-calcareous and slightly humic sand. It has an estimated sand fraction of 95% and a sand median of 112 µm and is very well to well sorted. The sand median of the fine and medium category are 105 and 172 µm over 281 and 32 intervals, respectively. Mica has been found in 90% of all sand intervals: half of the intervals contain small amounts of mica, while others contain traces or large amounts. In two third of all intervals, traces to small amounts of

glauconite are present. The colour of the sand is very variable and can be yellowish brown, or yellowish, brownish, greenish or olive grey.
Of all sand intervals, 54% has been described as bedded, and in 22% thin beds of detritus, clay or loam are present. Sublayers occur in 20% of the intervals. Three quarters of the sublayers consist of detritus, while the rest is made up of clay and loam.

A.6.11 Grain size analysis

Results of grain size analyses performed on samples from this lithofacies can be found in *Table A.*. Clay within the fine glacial outbreak deposits is very sandy and slightly humic, some samples are very or extremely silty. The admixed sand has a median of 113 µm with very fine sand as its most common sand median class (45%), although grains from classes up to extremely coarse are present in the samples.
Loam is very sandy and slightly humic. Most of the admixed sand belongs to the extremely fine (66%) sand median class, but grains up to very coarse are present. The sand median of the admixed sand (88 µm) is much lower than that of sand admixed in the clay or sand samples themselves.
The sand is very well sorted and slightly silty and humic, although some samples contain higher amounts of silt and clay. Most of the grains are very fine (34%), extremely fine (24%) and medium fine (23%) – grains larger than medium coarse are almost not present. All sand categories are slightly silty and slightly humic, although the fine category has a slightly higher clay and silt content. The most important median class in the fine category is very fine sand (38%), whereas for the medium category this is medium fine sand (33%).

Table A.24. Results of grain size analyses on the Peelo Formation, fine glacial outbreak deposits.

ogy or	Analysis (n)		Median (%)				Sand Median	
Sand cat.	Grain size	Org. comp.	Clay	Silt	Sand	Organics	D50 (µm)	CU
Clay	6	6	10.87	38.13	51.03	1.54	112.93	1.74
Loam	10	10	9.57	54.35	35.29	0.86	88.19	1.47
Sand	184	180	0.79	4.55	94.59	0.51	133.76	1.64
sand fine	126	122	1.08	7.19	91.96	0.53	119.08	1.6
sand medium	55	55	0.42	2.48	96.98	0.41	171.28	1.72

A.6.12 Peelo Formation – subglacial massive deposits

In two of the TopIntegraal cores, glacial tills interpreted as Peelo Formation have been described. Both cores were taken in the Groningen study area.

A.6.13 Core description

In both cores, this lithofacies consists of very homogeneous sands, on average consisting of 2% gravel, 93% sand, 6% silt, 2% clay and 2% organic material. There are lithological differences between the cores that may be due different origin of the local ice mass; one contains mostly fine sands and traces of mica and glauconite, whereas the other contains medium coarse sand and lacks mica or glauconite. Of all intervals, 40% contain small sand beds or sand lenses.

A.6.14 Grain size analysis

In contrast to the glacial till of the Gieten Member, this diamict is mainly composed of sand and contains very little clay. A single clay sample was analysed, indicating that clays are very sandy, slightly humic and contain medium coarse sand.

Sand samples (Table A.) are slightly silty and slightly humic, with a median of 281 µm and a very large spread. Most of the sand is extremely coarse (33%) while all other classes are represented by 12-14% of the sediment.
All sand falls within the categories of medium and coarse sand, which are both slightly silty and slightly humic. The coarse category has a higher sand fraction of 97%, and has a sand median of 389 µm and is very poorly sorted. The medium sand category also has a high sand fraction (95%) and a median of 258 µm and is also very poorly sorted.

Table A.25. Results of grain size analyses on the Peelo Formation, glacial till deposits. Compositional percentages and sand characteristics (sand median and uniformity coefficient) are median values (D50-percentile) of the sample data, shown only if 5 or more analyses have been performed.

Lithology or	Analysis (n)		Median (%)				Sand Median	
Sand cat.	Grain size	Org. comp.	Clay	Silt	Sand	Organics	D50 (µm)	CU
Sand	19	19	0.64	4.24	95.19	0.44	280.91	3.53
sand medium	13	13	0.68	4.58	94.74	0.44	257.7	3.4
sand coarse	6	6	0	3.08	96.84	0.28	389.11	4.13