NAM

Geological schematisation of the shallow subsurface of Groningen. For site response to earthquakes for the Groningen gas field.

Deltares

Datum Juni 2015

Editors Jan van Elk & Dirk Doornhof

General Introduction

The accelerations experienced at surface as a result of the earthquakes induced by the production of gas from the Groningen field is locally dependent on the shallow geological and soil conditions. This is called the site response effect. NAM has therefore asked Deltares to build a detailed model of the shallow subsurface below Groningen.

This report prepared by Deltares describes the quaternary geology of the Groningen area. In preparing this model of the shallow subsurface below Groningen, Deltares has made use 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.

Deltares is currently performing site response measurements near the geophone and accelerometer stations of the extended geophone network. These measurements combined with the current study will form the basis for the next update of the Ground Motion Prediction methodology, which will include site response based on the local soil conditions.

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".

The work by Deltares has been reviewed by a team of independent experts in quaternary geology.

External Expert	Affiliation	Role	Main Expertise Area
Adriaan Janszen	Exxonmobil	Independent Reviewer	Shallow Geological Model
Eric Meijles	University Groningen	Independent Reviewer	Shallow Geological Model
Joep Storms	TU Delft	Independent Reviewer	Shallow Geological Model
Tijn Berends	Student; University Groningen	Independent Reviewer	Site Response and Shallow Geological Model

Comments and suggestions made by the reviewers has been incorporated in the final version of the report.

<table>
<tr><td rowspan="2">Title</td><td colspan="2" rowspan="2">Geological schematisation of the shallow subsurface of Groningen. For site response to earthquakes for the Groningen gas field.</td><td>Date</td><td>June 2015</td></tr>
<tr><td>Initiator</td><td>NAM</td></tr>
<tr><td>Autor(s)</td><td>Pauline Kruiver, Ger de Lange, Ane Wiersma, Piet Meijers, Mandy Korff, Jan Peeters, Jan Stafleu, Ronald Harting, Roula Dambrink, Freek Busschers and Jan Gunnink</td><td>Editors</td><td colspan="2">Jan van Elk
Dirk Doornhof</td></tr>
<tr><td>Organisation</td><td>Deltares</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>
<u>Comment:</u>
The accelerations experienced at surface as a result of the earthquakes induced by the production of gas from the Groningen field is locally dependent on the shallow geological and soil conditions. This is called the site response effect. NAM has therefore asked Deltares to build a detailed model of the shallow subsurface below Groningen.</td></tr>
<tr><td>Directly linked research</td><td colspan="4">Introducotry text: “De ondergrond van Groningen: een geologische geschiedenis” by Erik Meijles of the Rijksuniversiteit Groningen
Site-Response measurements near the geophone / accelerometer stations of the extended monitoring network.</td></tr>
<tr><td>Used data</td><td colspan="4">GEOTOP Beta-version and CPT data sourced through Fugro and Wiertsema.</td></tr>
<tr><td>Associated organisations</td><td colspan="4">Department of geography of the natural environment of the Rijksuniversiteit Groningen
TNO Geologische Dienst Nederland (TNO-NITG)</td></tr>
<tr><td>Assurance</td><td colspan="4">The work by Deltares has been reviewed by a team on independent experts in quaternary geology; Adriaan Janszen (Exxonmobil), Eric Meijles (Rijskuniversiteit Groningen) and Joep Storms (TU Delft).</td></tr>
</table>

Enabling Delta Life

Geological schematisation of the shallow subsurface of Groningen

For site response to earthquakes for the Groningen gas field

Geological schematisation of the shallow subsurface of Groningen

For site response to earthquakes for the Groningen gas field

Pauline Kruiver
Ger de Lange
Ane Wiersma
Piet Meijers
Mandy Korff
Jan Peeters
Jan Stafleu
Ronald Harting
Roula Dambrink
Freek Busschers
Jan Gunnink

1209862-005

Deltares

Title
Geological schematisation of the shallow subsurface of Groningen

Client	**Project**	**Reference**	**Pages**
Nederlandse Aardolie Maatschappij B.V.	1209862-005	1209862-005-GEO-0004	219

Keywords
Shallow geology, heterogeneity, earthquakes, subsurface model, site response, sensitivity, amplification, Groningen Province

Summary
The NAM is preparing a new "Winningsplan", to be submitted in 2016. For this new Winningsplan, a new generation of Ground Motion Prediction Equations (GMPEs) will be developed. The overall scope is to reduce uncertainties in the hazard and risk analysis by improvement of input data, such as Groningen-specific data, and better GMPEs. In the current GMPE, only one value for shear wave velocity (V_s) is used for the entire Groningen field (V_{s30} = 200 m/s). The shallow subsurface of Groningen, consisting of Holocene and Pleistocene sediments is heterogeneous, resulting in variations of shear wave velocity. It is expected that part of the uncertainties in the seismic hazard and risk analysis can be reduced by including Groningen-specific information and knowledge of the subsurface to improve quantification of the site response caused by earthquakes.

Deltares has built a geological model for the Groningen field (+ 5 km buffer) for the purpose of the construction of V_{s30} maps and as input for the calculations of site amplification. These results will feed into the new GMPEs. The Geological model for the Site response at the Groningen Field (GSG-model) is, among other data sources, based on the beta version of GeoTOP (a 3D geological model of the Netherlands), provided by TNO Geological Survey of the Netherlands. The GSG-model built by Deltares consists of a map defining geological areas and voxel stacks containing stratigraphy and lithological class with depth. Additionally, a state-of-the-art V_{s30} map was derived for the Groningen field + 5 km buffer, taking into account Groningen-specific V_s relations and the geology from the GSG-model.

This report describes the method for the construction and the results of version 1 of the GSG-model, the quality checks performed on the model and recommendations for future versions. When more data becomes available, updates of the GSG-model are anticipated.

References
Contract UI46802 "Studies on the soil in Groningen"

Version	Date	Author	Initials	Review	Initials	Approval	Initials
5	16 March 2015	Pauline Kruiver		Bert van der Valk		Bob Hoogendoorn b/a	
		and others					

1209862-005

Deltares

Title
Geological schematisation of the shallow subsurface of Groningen

Client	**Project**	**Reference**	**Pages**
Nederlandse Aardolie Maatschappij B.V.	1209862-005	1209862-005-GEO-0004	219

Versions

Version	Status	Date
1	Table of contents for internal reviewer	30 October 2014
2	Internal draft	14 December 2014
3	Draft for review commission	14 January 2015
4	Draft version 2 for Groningen Scientific Board	10 March 2015
5	Final	16 March 2015

State
final

Contents

1 Introduction

1.1 General setting

The motivation for the construction of the **G**eological model for the **S**ite response at the **G**roningen Field (GSG-model) is the updated "Winningsplan", to be submitted by NAM in 2016. The area of interest includes the extent of the Groningen gas field plus a 5 km buffer around it (Figure 1.1).

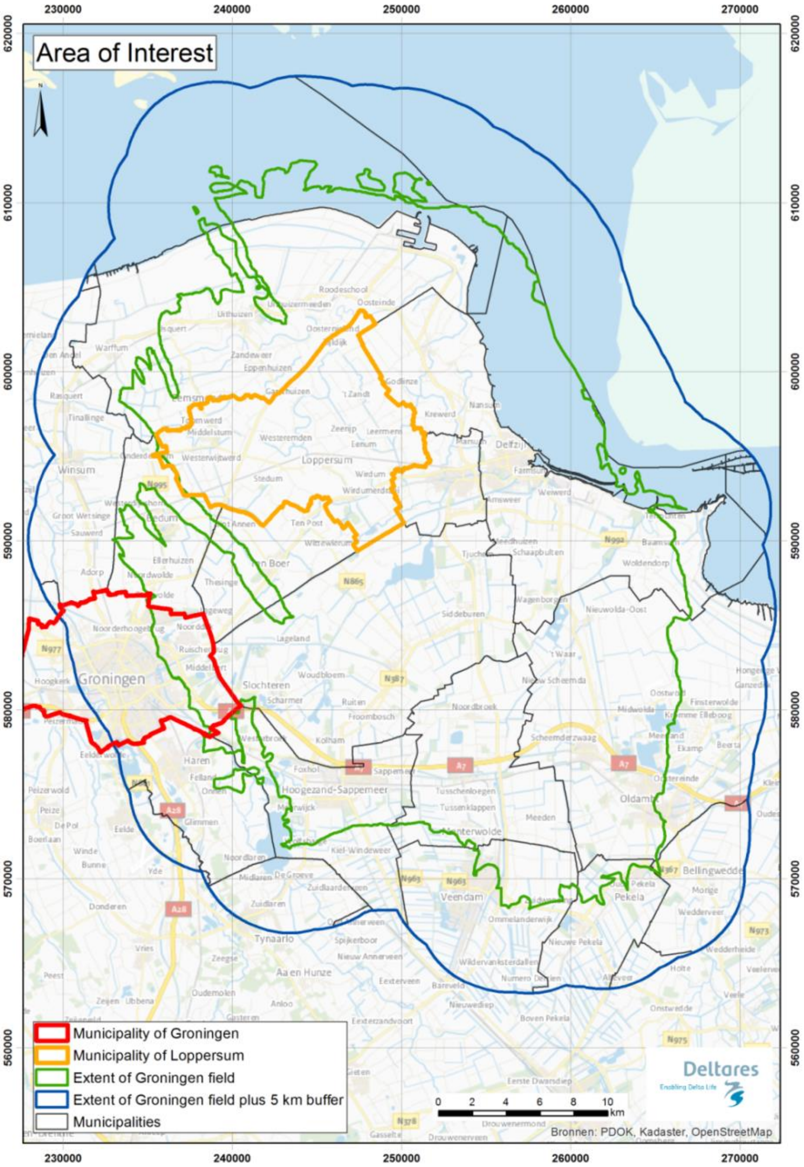

Figure 1.1 Area of interest showing the extent of the Groningen gas field and a 5 km buffer zone. The boundaries of the municipalities are shown, including the boundaries of the municipality of Loppersum (orange) and Groningen (red), both of which are pilots.

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 structures in the near surface and on the surface at shaking of the ground, e.g. the response of a building due to an earthquake.

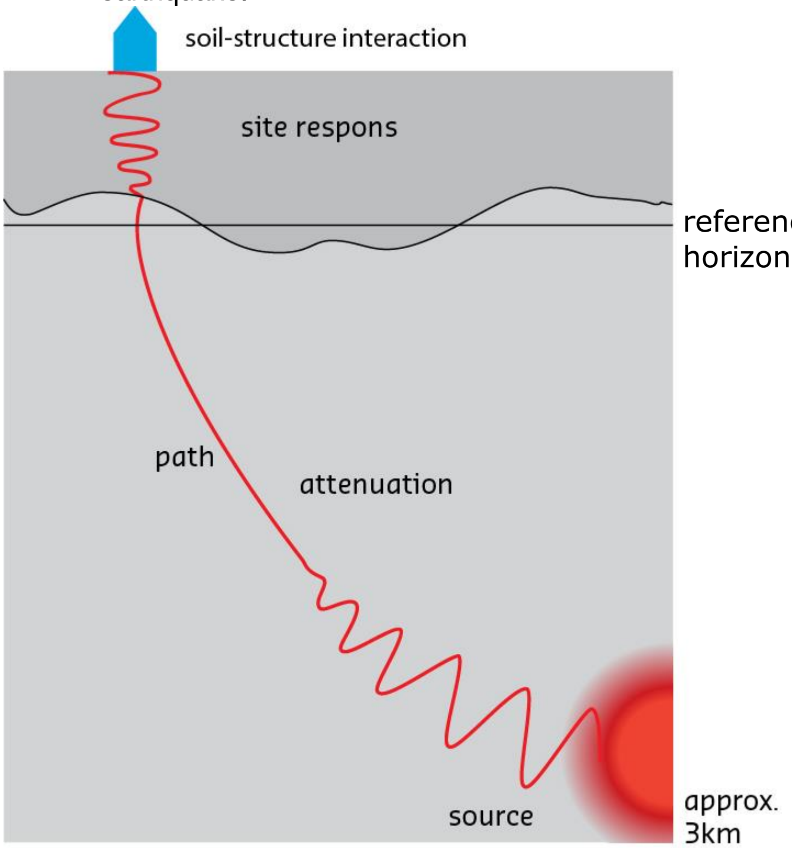

Figure 1.2 Sketch showing the effect of an earthquake on the surface via the route of source, path, site response and soil-structure interaction. The source and path effects act in the bedrock, while the site response acts in the top layer of soft sediments. For site response calculation it is usually assumed that the soft sediments are present in the top 30 m, while in reality these sediments can be present at shallower or larger depths.

The activities of Deltares 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 soil-structure interaction. Obviously, the interfaces are not that sharp. The transition between the deep/bedrock part and the soft sedimentary infill responsible for the site response is the “reference baserock horizon”. Currently, the depth of the reference baserock horizon has not yet been defined. The possibilities are currently being discussed by experts from NAM, Shell and Deltares. Before performing the site response calculations for the Groningen field in the next phase of the project, the reference baserock horizon will be defined. In the preliminary sensitivity analyses performed at the start of the project, we have used a working depth of 30 m below the surface. From a physical point of view, the reference baserock horizon should be located at a depth where a contrast in acoustic impedance occurs. The base of the Peelo Formation might represent such a physical boundary. Therefore, the maximum extent of the version 1 GSG-model is 200 m or the base of the Peelo Formation whenever that extends deeper than 200 m (max NAP-235 m). In this context, “shallow” indicates a maximum of 235 m depth containing relatively soft sediments.

As part of the path to the updated “Winningsplan” for the Groningen field, a new generation of Ground Motion Prediction Equations (GMPE) will be developed. Overall scope is to reduce uncertainties in hazard and risk analysis by improvement of input data, such as better GMPEs and addition of Groningen-specific data. The new generation GMPEs consists of various options that will be derived specifically for the Groningen field. The new GMPEs will include site specific V_{s30} values and site response calculations across the field (Bommer, 2014).

The scope of this report is to provide Groningen-specific data in the form of a regional 3D geological model and a regional map of V_{s30}. At this stage of the project, Deltares has constructed version 1 of a regional geological model of the shallow subsurface of the Groningen field for the purpose of making preparations to determine the site amplification effect (GSG-model – version 1) and constructed a V_{s30} map based on this model.

The GSG-model was constructed by a team of geologists from Deltares and TNO. The team consisted of:

- Deltares: Ger de Lange, Ane Wiersma, Pieter Doornenbal, Tommer Vermaas, Renée de Bruijn, Marc Hijma, Pauline Kruiver (project leader).
- TNO: Jan Stafleu, Freek Busschers, Marcel Bakker, Ronald Harting, Roula Dambrink, Willem Dabekaussen, Wim Dubelaar, Eppie de Heer, Jan Gunnink.

1.2 Version 1 of GSG-model

This report presents version 1 of the GSG-model. It is a state-of-the art model, based on the current knowledge and the available data sources described in chapter 3. As new data becomes available continuously, updates of the GSG-model are planned for in the future. This will lead to the release of new versions of the GSG-model.

Version 1 of the GSG-model consists of:

- A GSG-model for site amplification covering the Groningen field + 5km buffer in two different depth ranges:
  - Surface level to NAP- 50 m (NAP is Dutch Ordnance Datum). This part of the model consists of a set of shapefiles of geological areas (x-y extent) and GeoTOP voxel stacks (depth extent) based on the beta version of GeoTOP.
  - Depth level of NAP-50 m to approx. NAP-200 m. This part of the model consists of another set of shapefiles of geological areas (x-y extent) and scenarios of subsurface composition (depth extent).
- A look up table for shear wave velocity (V_s) values based on 60 Seismic Cone Penetration Tests (SCPT) located in the area of interest.
- A V_{s30} map of Groningen + 5km buffer based on the beta version of GeoTOP and the Groningen-specific look up table for V_s constructed from SCPTs.
- Part of Groningen municipality falls outside the area of interest (Figure 1.1). Only the part that falls within the area of interest is covered in the GSG-model.

Recommendations for future versions of the GSG-model are included at the end of each chapter and summarised in chapter 8.

1.3 Reader's guide

The report is structured as follows. Chapter 2 describes the background of the general shallow geology of Groningen and its relation to site response to shaking by earthquakes. Chapter 3 sums up the available background information used for the construction of the Groningen subsurface model. In chapter 4, the method of schematisation is explained. Chapter 5 describes the results of two quality checks. The first quality check was performed during schematization for the municipality Loppersum pilot (section 5.2). The second quality check was made after completion of the schematization for the entire Groningen field (+ 5 km buffer) for the surface to 50 m depth part (section 5.3). The resulting GSG-model for the Groningen field (+5 km buffer) is provided in chapter 6. Maps showing the shear wave velocity distribution for the top 30 m, derived from the GSG-model, are shown in chapter 7. In the last chapter (8), we give recommendations for future developments and updates of the GSG-model. Descriptions of abbreviations and terminology used in this report are provided in Appendix A.

1.4 Disclaimer

The geological schematization has been performed with the information available at the time of performing the work (September – November 2014). This means that a beta version of GeoTOP of TNO – Geological Survey of the Netherlands was used. TNO anticipates significant differences between the beta version and the final version to be released not earlier than the second quarter of 2015. The impact of differences in outcomes between those of the beta version and those of the first official release of GeoTOP is described in section 3.4. Changes that might occur could affect the boundaries of geological areas and the infill of voxel stacks in terms of e.g. stratigraphic unit. Additionally, not all CPT information has been included until the moment of reporting due to late delivery at a time that the process of schematisation had already started.

The scale of the geological area map is linked to the size of the voxels of GeoTOP. Voxels are comparable to pixels in a grid, but also have a thickness. A vertical succession of voxels is called a voxel stack. The voxels in GeoTOP measure 100 m x 100 m in the horizontal direction and 0.5 m in the vertical direction. The GeoTOP model is based on observations (borehole records) of the subsurface. The data density, however, is spatially highly varying. Parts of the GeoTOP model are based on limited amounts of data. Although the GeoTOP model is available on the level of detailed voxel stacks, it is a regional model. Therefore, the site amplification derived for each voxel stack does not necessarily give the true site amplification of that voxel stack if measured. Site response is sensitive to depths and thicknesses of soft sedimentary layers. By defining geological areas of similar build up, all relevant variations in depth and thickness of these layers are included in the voxels stacks of that area. Therefore, results need to be aggregated to geological area scale, instead of individual voxel stack scale.

The boundaries of the geological areas are represented by sharp lines on the map. In reality, variations in geological build up are gradual. Therefore, the boundaries of the geological areas are probably gradual as well. This aspect needs to be investigated as soon as the site response results for a pilot area will be available.

2 Background

2.1 General shallow geology of Groningen

The description of the geological history in terms of age and depositional environment is given as the outcome of geological mapping and dedicated research. It is based on (the many sources in) De Mulder et al. (2003), supplemented with information from Vos (2013) and Vos et al. (2014).

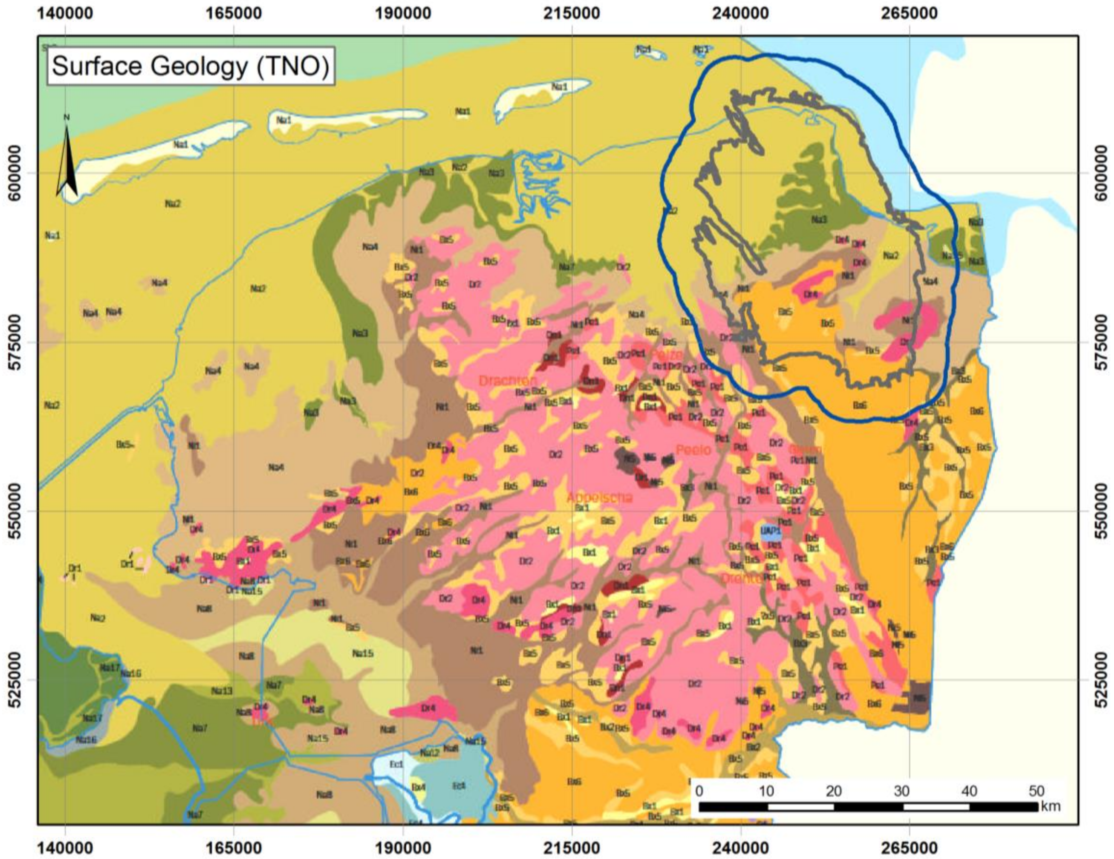

Figure 2.1 Geological map of the northern part of the Netherlands (level of detail on scale 1:600:000), showing geological formations at or near the surface (source: TNO Geological Survey of the Netherlands, De Mulder et al., 2003). Nomenclature for formations in https://www.dinoloket.nl/nomenclator. In the area of interest: Naaldwijk Formation (Na2 – yellow-green, Na3 - green, Na4 - pale brown), Nieuwkoop Formation (Ni1 - brown), Boxtel Formation (Bx6 – orange, Bx5 - pale orange) and Drenthe Formation (Dr4 - pink). The map and legend can be found on: http://www2.dinoloket.nl/data/download/maps/images/geologische%20overzichtskaart%20van%20 Nederland%202010.pdf.

The surface geology is shown in Figure 2.1. An overview of Dutch lithostratigraphic units is provided in Figure 2.2. A series of Formations and Members describes the deposits resulting from the Holocene development, separating coastal-marine clastic units from inland organic units. The Formations and Members relevant for the northern part of the Netherlands are shown in Table 2.1. The descriptions of the Formations are included in Appendix G (in Dutch). The relevant lithofacies for the northern part of the Netherlands are shown in Table 2.2.

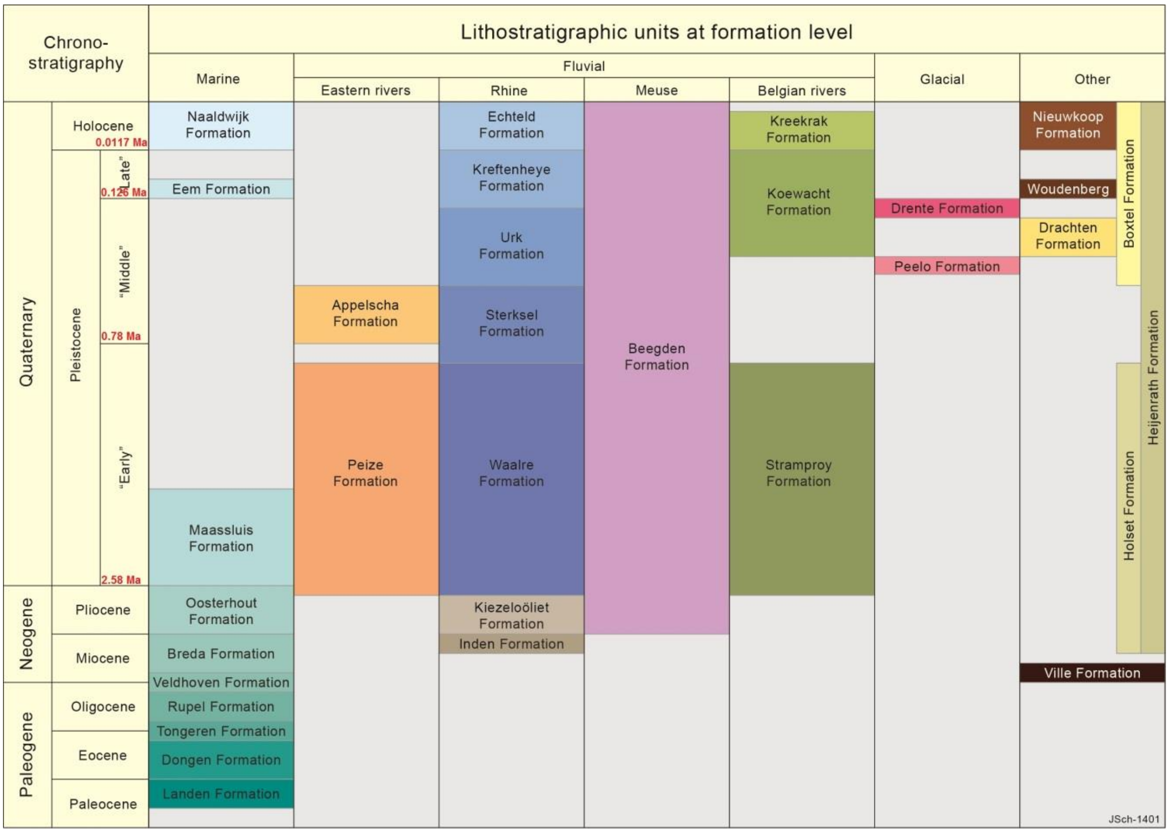

Figure 2.2 Overview of Dutch lithostratigraphic units in the shallow subsurface (Source: TNO Geological Survey of the Netherlands. Adapted from https://www.dinoloket.nl/overzichtstabel). For details on Formations, see Appendix H (in Dutch). Ages of Quaternary chronostratigraphy indicated in red (Cohen et al., 2013).

Table 2.1 Overview of Formations relevant for the northern part of the Netherlands.

Anthropogenic deposits	
AAOP	Anthropogenic deposits
Naaldwijk Formation	
NASC	Naaldwijk Formation, Schoorl Member
NAZA	Naaldwijk Formation, Zandvoort Member
NA	Naaldwijk Formation, no differentiation between Wormer and Walcheren Members
NAWA	Naaldwijk Formation, Walcheren Member
NAWO	Naaldwijk Formation, Wormer Member
Nieuwkoop Formation	
NINB	Nieuwkoop Formation, Nij Beets Member
NIHO	Nieuwkoop Formation, Hollandveen Member
NIBA	Nieuwkoop Formation, Basal Peat Bed

Boxtel Formation	
BX	Boxtel Formation
BXKO	Boxtel Formation, Kootwijk Member
BXSI1	Boxtel Formation, Singraven Member, upper unit
BXWI	Boxtel Formation, Wierden Member
BXSI2	Boxtel Formation, Singraven Member, lower unit
Other units	
EE	Eem Formation
DR	Drente Formation
DRGI	Drente Formation, Gieten Member
DN	Drachten Formation
URTY	Urk Formation, Tynje Member
PE	Peelo Formation
UR	Urk Formation, Tynje Member
ST	Sterksel Formation
AP	Appelscha Formation
PZWA	Peize and Waalre Formations (Peize in this area)

Table 2.2 Lithofacies relevant for the northern part of the Netherlands

Lithofacies code	Sedimentary environment	General lithology	Period	Stratigraphic notes
Pfsf	Fluvial channel belt	Fine sand	Pleistocene	Various
Pfsm	Fluvial channel belt	Medium coarse sand	Various	Various
Pfsc	Fluvial channel belt	Coarse to very coarse sand	Various	Various
Pxlp	Various	Low permeability, clay/loam	Various	Various
Pasf	Cover sand	fine sand	Boxtel	BXWI
Pvsm	Streamlet	Medium to coarse sand	Boxtel	BX without clay/loam/peat
Pvbd	Streamlet	Fine sand, loam, clay & peat (very diverse)	Boxtel	BXSI with clay/loam/peat
Pgcs	Glacial Till	Loam, sandy clay, gravelly, occasional sand inclusions	Drente	Glacial (Drente/Peelo)
Pgsc	Fluvioglacial	Coarse gravelly sand, gravelbeds, boulders	Drente	Drente Schaarsbergen
Pgcc	Potclay, glaciolacustrine clays	Clay, compact, occasional fine sand beds	Peelo	Peelo Nieuwolda
Pgsf	Glacial outbreak	Fine sand	Peelo	Peelo
Ptsc	Channel	Sand (clayey or silty), usually fine	Eem	Tidal (Eemian)
Ptsm	Channel	Medium coarse sand	Eem	
Ptcc	Mudflat	Clay, some sand/silt beds	Eem	
Pxpp	Swamp/Marsh	Peat	Eem	
Tfcc	Mudflat	Clay	Holocene	Tidal/Marine
Tfcp	Supratidal	Organic clay and peat alternations	Holocene	
Tfsc	Mudflat channels	Clay and sand, alternating	Holocene	
Tfss	Sandflat	Sand (clayey)	Holocene	
Tcsf	Channel belt	fine sand (clayey)	Holocene	
Tcss	Channel belt	fine, medium sand	Holocene	
Tcsm	Estuarine channel belt	medium sand (clayey)	Holocene	
Tccs	Channel fill	Clay sandy	Holocene	
Shpp	Swamp/Marsh	Peat, amorphous to not-amorphous	Holocene	Holland Peat
Sbpp	Swamp/Marsh	Compacted peat	Holocene	Basal Peat
Aaop	Landfill	various (clay, loam, sand, peat, concrete, rubble, wood)	Holocene	Anthropogenic

The shallow subsurface (upper 200 meters) of the Province of Groningen and surroundings, holds deposits of the last 1 million years. Stratigraphically, this means that it contains sediments from the youngest half of the Pleistocene onwards (Figure 2.2). During this time 10 periods with an ice-age climate occurred, but only during two major glaciations the Scandinavian ice-sheet grew large enough to cover the Northern Netherlands. Around 450,000 years (maximum) and around 150,000 years ago respectively, the landscape was covered by ice. The deposits of these two glacial episodes are important as dividers of the geological build up. They can be recognised very well in boreholes and cone penetration tests. As such, they provide clear anchor points upon which the GSG-model is based.

The first glaciation in the northern part of the Netherlands is known as the Elsterian glaciation and amongst others produced deep subglacial features known as ‘tunnel valleys’. These valleys were filled with sands and clays during the glaciation (the Peelo Formation in Figure 2.2) and were buried by younger sediments. The second glaciation is known as the Drenthe Substage glaciation of the Saalian glacial. It produced the till sheet that constitutes the Drenthe plateau, the aligned ridges along its north-eastern edge known as the Hondsrug, and broad melt water-valley structures to the east of it (used by the Hunze and Ems rivers since). The ridge-and-valley topography is still present in the landscape stretching from the city of Groningen towards the South-East. The Drenthe Substage is also known as the penultimate ice-age.

During the last ice-age (known as the Weichselian), Scandinavian ice-sheets covered parts of Denmark and north-eastern Germany, but did not reach the Netherlands. Instead, at maximum cold in the Last Glacial, polar-desert ‘periglacial’ environments prevailed. This was the case lastly between 25,000 and 14,000 years ago, when a widespread superficial blanket of eolian sand formed that in many places marks the top of the Pleistocene deposits (the so-called cover sands). Such environmental conditions have also prevailed in earlier glacial periods, for example around 70,000 years ago at the beginning of the last glacial and around 170,000 and 140,000 ago before and after the Saalian glaciation episode. Besides eolian activity, local river systems fed by snow melt are present at these times. After floods, these periglacial sands and silts in the many local rivers provided source areas for cover sand nearly everywhere. These deposits constitute the Boxtel Formation in Figure 2.2.

The northern part of the Netherlands borders the North Sea. During interglacial periods, when sea-level was higher than during ice-ages, a large part of Groningen formed the coastal plain of this sea. This is the case in the current interglacial (Holocene, 11,700 years BP till present), as was the case in the last interglacial (known as the Eemian, around 120,000 years ago), and to a lesser degree has also been the case during older interglacials. The coastal plains

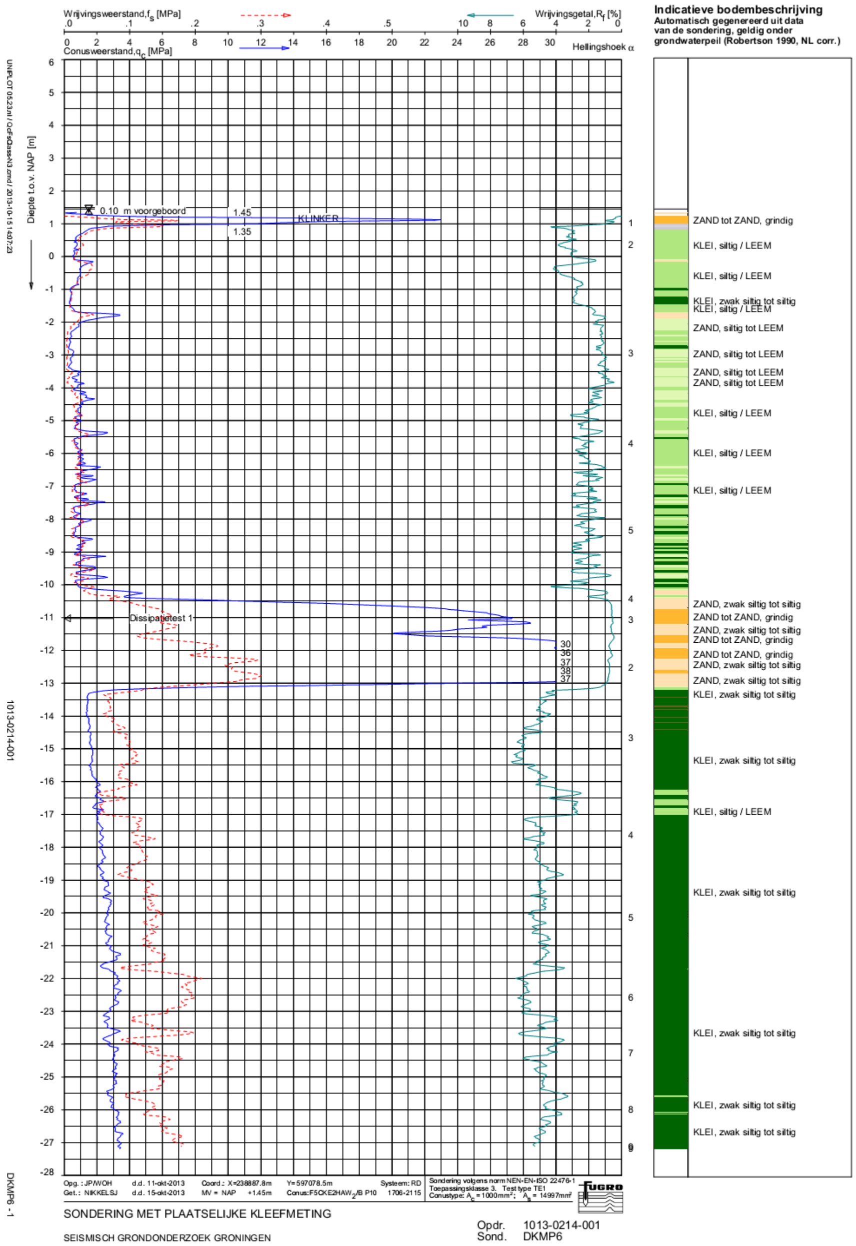

Figure 2.3 Example of a cone penetration test record taken at the KNMI accelerometer station Middelstum (BMD2) showing a typical sequence of Holocene coastal plain deposits (intermittent soft clay and sand beds) from surface level to 10 m below NAP overlying dense sands of the Boxtel Formation down to 13.3 m below NAP, overlying stiff clays of the Peelo Formation. Comments in the figure are in Dutch.

established themselves during stages of transgression, driven by sea-level rise at the end of each ice age and beginning of each interglacial. The coastal plains then developed and built out further during the remainder of the interglacial. For the Holocene transgression and high stand the developments are particularly well known. Peat beds and clay beds dominate in the margins of the former tidal basin. Sandy deposits occur more locally in former channels of the central part of the tidal basin. The lithologies of the coastal plain deposits overall are particularly heterogeneous and variable. Soil horizon development, both in the top of Pleistocene deposits and in the various Holocene deposits, is a further Holocene feature. This has resulted in stacked sequences of tidal clays and sands that are often thinly bedded and are intermittent with peat layers and soil horizons. An example of such a stacked sequence is shown in Figure 2.3. The spatial distribution of Holocene deposits is visualised in the geological cross-section through Groningen from north to south in Figure 2.4 (Vos, 2015, in preparation). This figure serves to show the complexity of the Holocene and Pleistocene deposits.

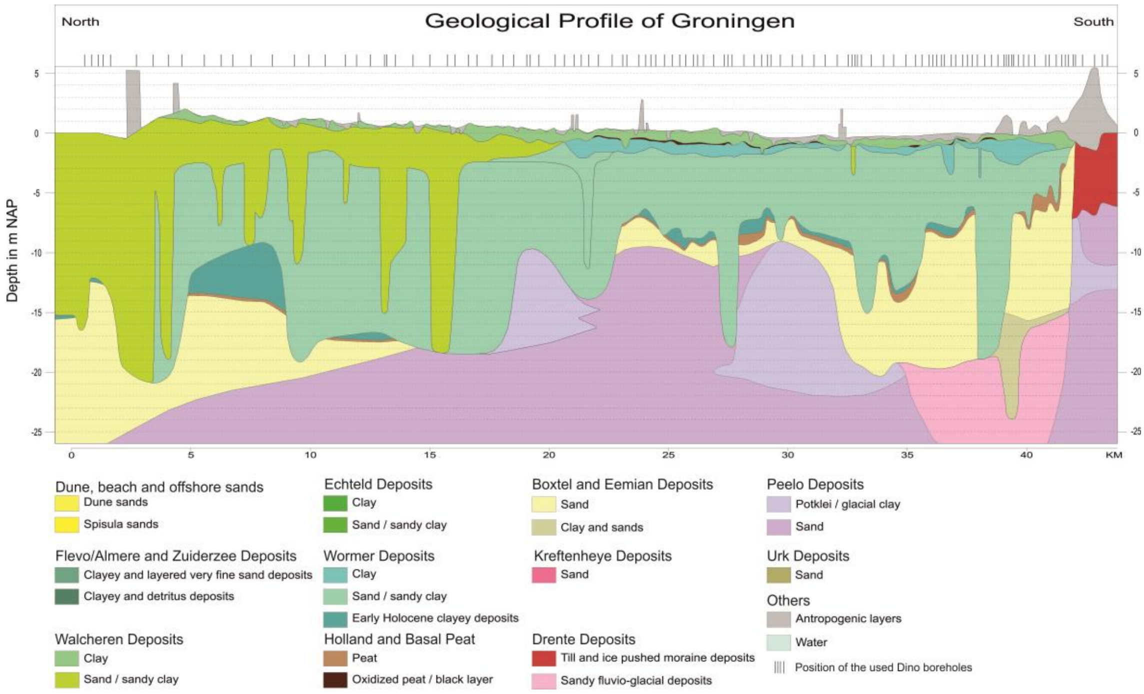

Figure 2.4 Example of a geological cross-section through the Holocene coastal deposits of the province of Groningen from North to South showing the full complexity of the Holocene and Late Pleistocene deposits relevant for the construction of the GSG-model. From Vos (2015, in preparation).

A particularity of the geological development in the youngest 3000 years is the influence of man in the coastal plain and the hinterland. Some of the human activities, especially those in the peat lands (cultivation as cropland, draining for use as meadows, mining for fuel) induced land subsidence, causing peat to disappear – a superficial process that is on-going even today. In the uplands, this makes Pleistocene surfaces reappear. In the lower parts of the coastal plain, this induced ingressions of the Wadden Sea into the Groningen coastal plain. In the centuries following such ingressions, silting up occurred and, in turn, lost coastal land area could be reclaimed. The effect on the landscape during the last 1000 years is schematically visualised in Figure 2.5 (Vos et al., 2014).

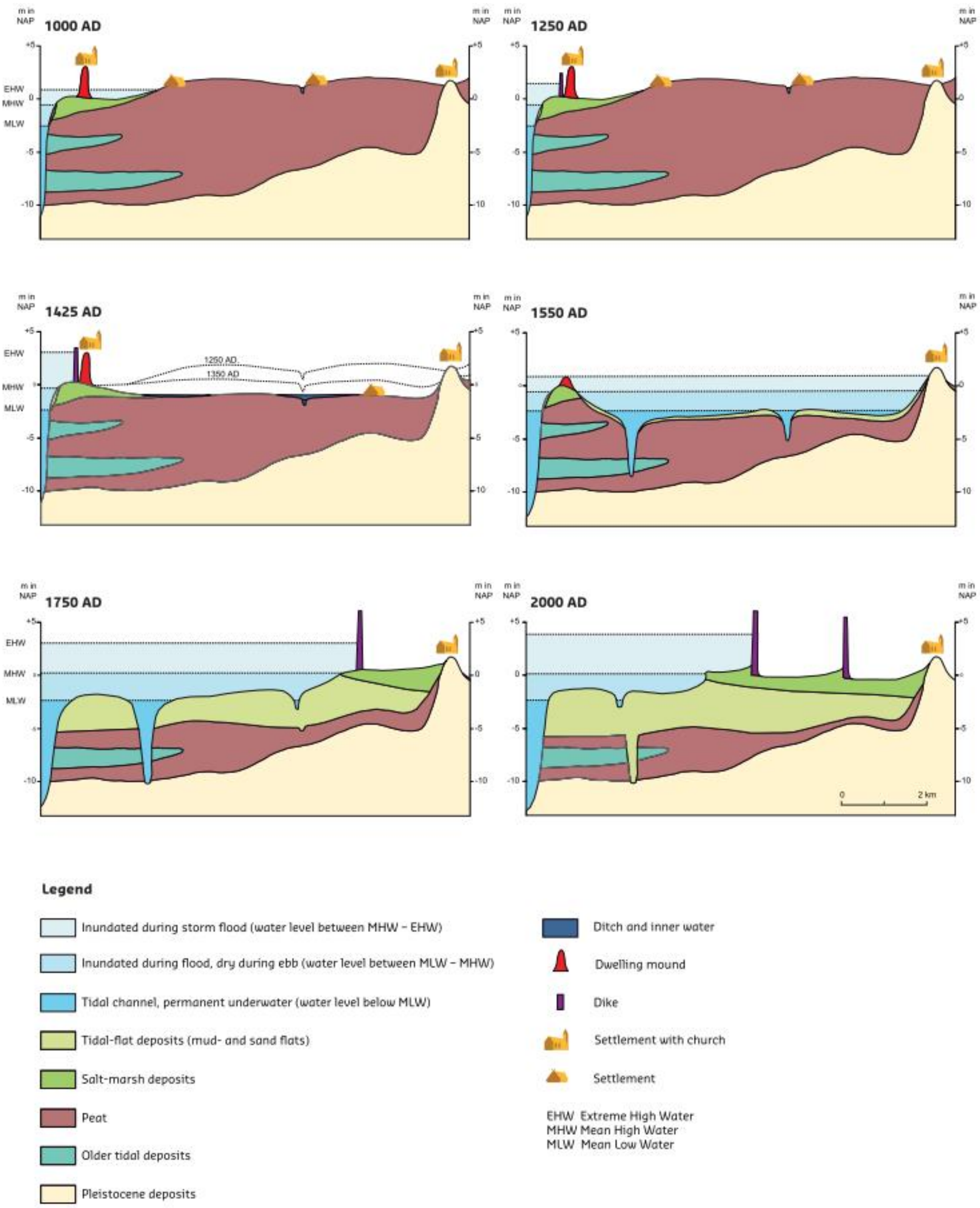

Figure 2.5 Schematic cross-section from north to south of through Groningen (Dollard region) between 1000 and 2000 AD. Illustration of the influence of man over time on the landscape. From Vos et al, 2014.

2.2 Site response to earthquakes

2.2.1 Link to geology

Subsurface mapping begins with identifying lithological contacts and tracing them through the area. A series of Formations and Members describes the deposits resulting from Pleistocene developments, separating deposits from glaciated environments from those formed in the periglacial environment, including aspects of provenance of the deposits.

The variations in depositional environment due to climatic changes of the ice ages were strong in the youngest 1 million year and in practice dominate the lithostratigraphical division schemes and mapping. Only at local scale, young Pleistocene features can be explained by spatial differences in land subsidence, related to fault systems and salt tectonics. The regional structures and patterns are first and foremost inherited from the Drenthe substage glaciation in the Pleistocene, the sea-level rise in the Holocene, and the activities of man. More local topographical and subsurface features are expressions of stream erosion, accumulations of cover sands, permafrost and ice-lens formation and melting, tidal creek morphology et cetera.

As such the distribution of the degree of site response is an expression of the distribution of the geological features mentioned above. The degree of the site response is strongly related to the stiffness and density contrasts of the shallow subsurface lithology. Therefore, the spatial patterns found in the analysis carried out for this report resemble the patterns of the transgressional and ingressional soft clay-rich sediments and peat layers in the low lying, northern part of Groningen versus the stiffer mainly glacially loaded formations in the southern part of Groningen (see Figure 2.6). The site effect distribution, whether it is described as the average shear wave velocity V_{s30}, an amplification factor or otherwise will also be determined by the thickness and depth of the respective layers. The distribution maps constructed for this study therefore show the patterns as seen in Figure 2.6 in a broad sense only, also taking into account the vertical build-up of the sub-surface.

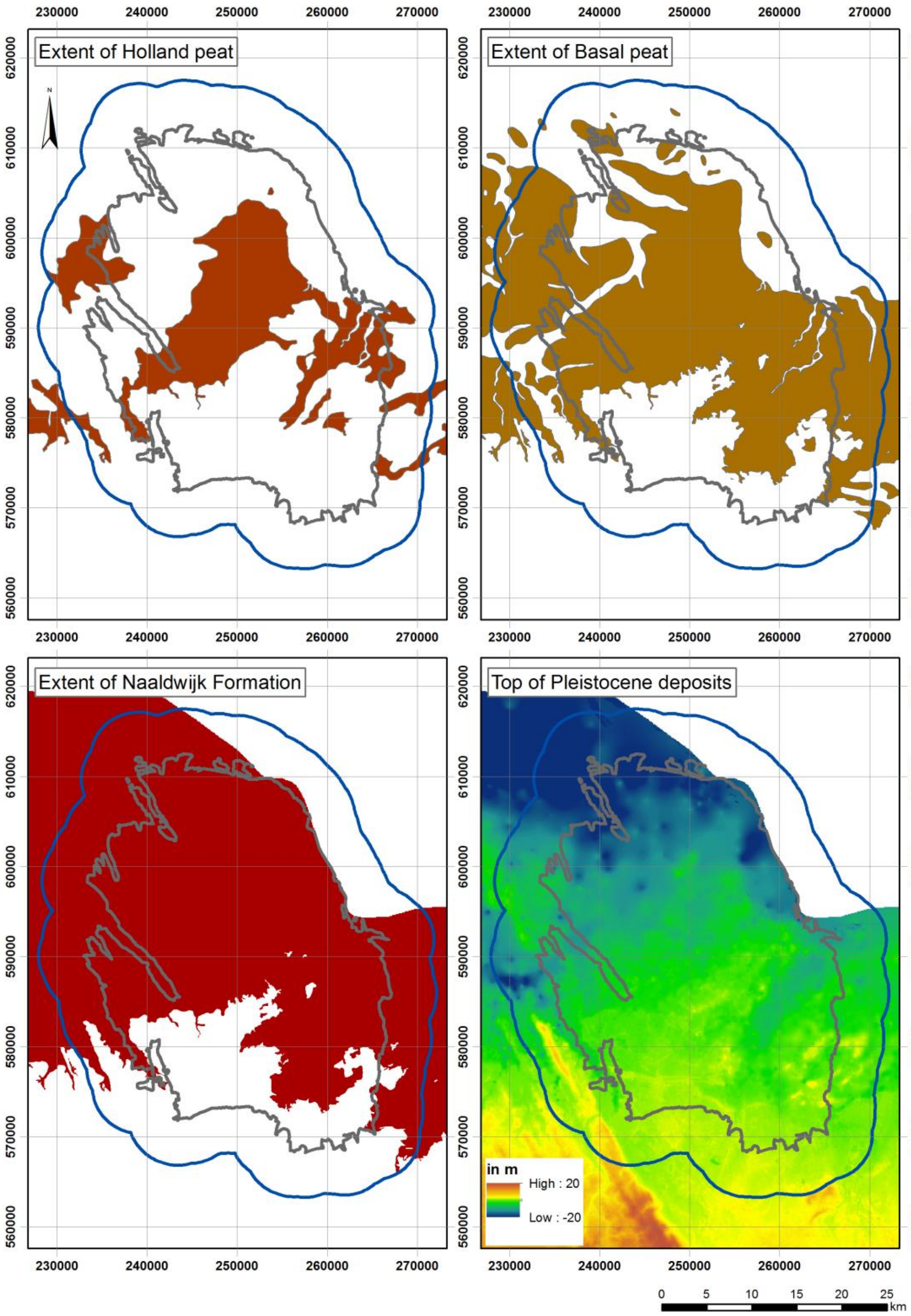

Figure 2.6 Extent of soft Holocene deposits (Naaldwijk Formation, Holland Peat and Basal Peat) and the topography of the Pleistocene surface relative to NAP (Source: TNO Geological Survey of the Netherlands).

2.2.2 Site response relations

In the current hazard and risk analysis for the Groningen gas field, the site amplification of the shallow subsurface is characterized by one fixed value of shear wave velocity (V_s) only. In the Akkar et al. (2014) approach for site response, the value of V_{s30} feeds into the equation to calculate site response. The parameter V_{s30} is the time averaged value of V_s over the top 30 m of the soil. This is a classical parameter for evaluating dynamic behaviour of the soil. However, the value of 30 m is rather arbitrary. It is accepted as a convention internationally and in the Netherlands. However, it is not necessarily linked to a characteristic depth of the major contribution of the shallow subsurface to the site amplification.

In the Ground Motion Prediction Equations (GMPE) of Groningen derived so far, the shallow subsurface is represented by a value of V_{s30} of 200 m/s for the entire Groningen field (NAM, Technical Addendum to the Winningsplan Groningen 2013). In general, shear wave velocities increase from peat layers (V_s ~ 50-100 m/s) to clay layers (V_s ~ 80-150 m/s) to sand layers (V_s up to 200 m/s for Holocene, higher values for Pleistocene). Still, compared to bedrock, the values of V_s for sedimentary layers are rather low. Due to the geological history of Groningen, there are distinct patterns of peat and clay present in the first tens of meters of the subsurface. This is illustrated in the geological map of the North of the Netherlands in Figure 2.1 and the more detailed maps of Figure 2.6. Because of the heterogeneity of sediments in the subsurface, we expect that V_{s30} values vary greatly. This is also in agreement with the simplified site response classification map of the Netherlands made by TNO and KNMI (Wassing and Dost, 2012). This map (Figure 2.7) only distinguished three classes of site response based on a limited set of V_{s30} measurements, namely stiff soils (V_{s30} > 200 m/s), soft soils (V_{s30} < 200 m/s) and special study soils (including e.g. peat layers thicker than 3 m and peat layers of 1 to 3 m embedded in stiff soil).

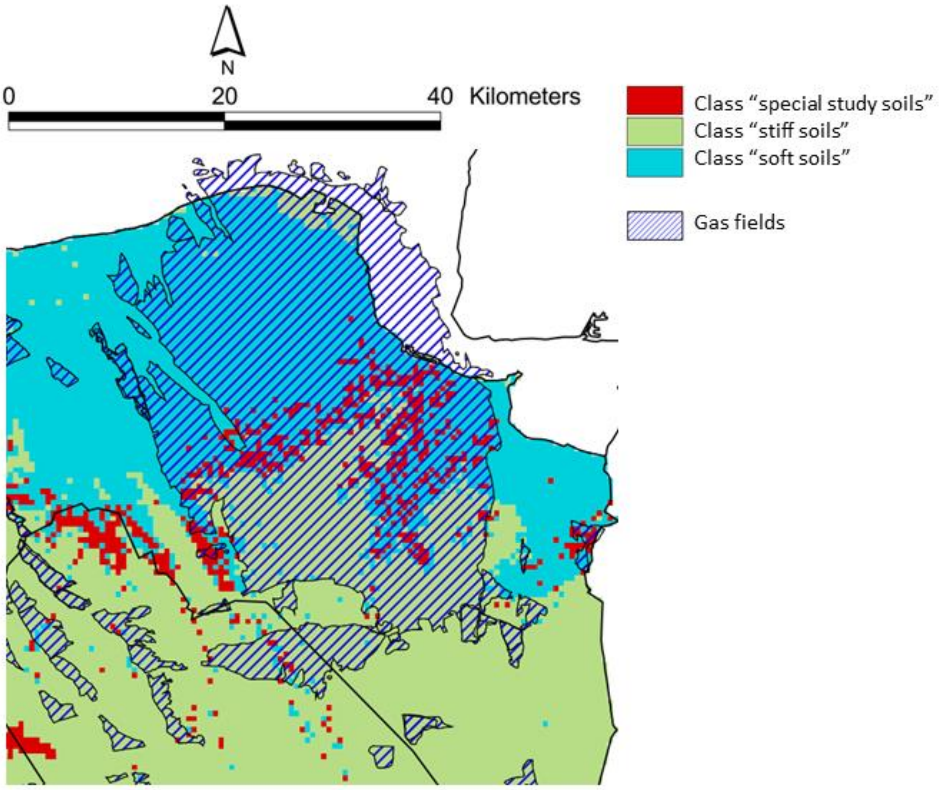

Figure 2.7 TNO Site Response – soil classification map for the Groningen field (source: segment of appendix 3 from Wassing and Dost, 2012).

The need for a spatial varying distribution of V_{s30}, rather than using a fixed value of 200 m/s, was acknowledged by NAM. Arup made a first attempt to construct a V_{s30} map for Groningen (Villano and Neto, 2013, page 27). However, their map (Figure 2.8) is based on a limited number of seismic CPTs and on conversion of sleeve friction and cone resistance from a limited number of CPTs to V_s values. Still, the general expected difference between the northern (lower V_{s30}) and southern part (higher V_{s30} values) is visible. Arup recommends improving their V_{s30} map by increasing data coverage.

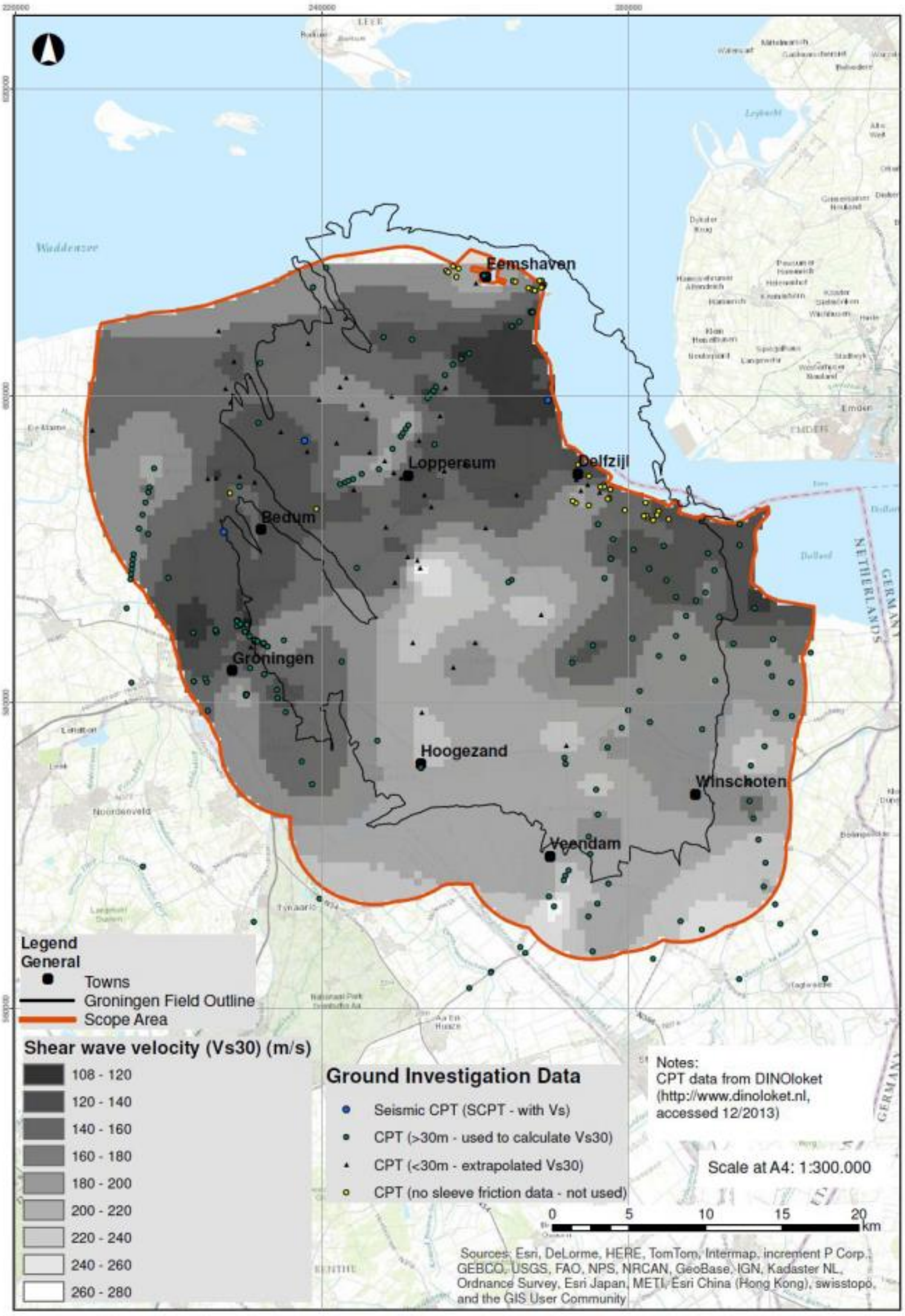

Figure 2.8 Arup map of V_{s30}, based on a limited amount of CPT and SCPT data. Source: Villano and Neto, 2013, page 27.

2.2.3 Site response calculations

A different approach in site response analysis is to calculate the response of a soil column to earthquake shaking by numerical methods. Common practice in geo-engineering is to use a 1D approach that models the soil response for an upward propagating horizontally polarised shear wave. There are various options for the calculation models: linear elastic (LE), equivalent linear elastic (EQL) and non-linear elastic calculation models. A large number of software packages for performing the soil response calculations is available. A selection of several frequently used programs for the different calculation methods is given Table 2.3.

Table 2.3 Overview of software programs for 1D calculations of site response

Calculation model	Software programs
Linear-elastic	Various
Equivalent linear-elastic	SHAKE, SHAKE91, SHAKE2000 EERA STRATA
Non-linear	Cyclic-1D Dmod2000 Deepsoil NERA Various Finite Element Methods (FEM) programs

The linear-elastic models assume that the soil behaves in a linear elastic way. However, the behaviour of the top soil layers during earthquake loading is non-linear. For example, an input level of shaking that is twice as strong does not necessarily result in shaking of the ground surface that is twice as strong. For realistic results, we need a model that includes this non-linear behaviour. Therefore, linear elastic models are discarded.

A full non-linear calculation model in principle captures the correct soil behaviour. This requires the use of a proper constitutive model, including the proper material parameters. The calculations are performed in time domain and may be time consuming.

An effective way to include non-linear soil behaviour and fast calculations is to use an equivalent linear elastic approach. The calculation model in this case is linear elastic. The soil parameters (i.e. strain dependent soil stiffness and material damping), however, are adjusted according to the calculated shear strain amplitude. The calculations are repeated until the used strain dependent soil parameters and the calculated shear strains converge. The first program using this approach was the program SHAKE (Schnabel et al., 1972). Since the seventies, this approach has become more or less the standard in the industry.

For the soil response calculations for the Groningen field (+5 km buffer), a large number of calculations needs to be performed. Therefore, a computational effective model and program is preferred. Therefore, we select the equivalent linear elastic approach. We tested different available equivalent linear programs. The final choice for the calculation program to be used in the site response analysis is STRATA (Kottke et al., 2013), for the following reasons:
- The flexibility in using various types of input signal (time domain signal, Fourier spectrum or response spectrum).
- The in-built option for Monte Carlo analysis.

The program STRATA is available at https://nees.org/resources/strata. Currently, the STRATA software is being adjusted to realise calculations in batch mode for the site response calculations for the Groningen field.

3 Sources of information

3.1 Overview of sources

For the schematisation of subsurface, several sources of information were available. Close cooperation between Deltares and TNO (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. In Appendix C, details about versions, references, use for schematisation and other potential uses are included. Additionally, several RGD/TNO (Geological Survey of the Netherlands) reports were used, as well as other literature such as Roeleveld (1974) and Van Staalduinen (1977).

Table 3.1 Sources of subsurface information available for schematisation

Dataset	Short description
Borehole records DINO	Database containing records (descriptions) from boreholes from the shallow subsurface (< 500 m depth). Both from manual as from mechanical borings.
Borehole logs	Logs of geophysical measurement performed in an open borehole. Possible parameters to be measured are temperature, gamma ray, short and long normal resistivity and seismic velocities.
AHN	Actueel Hoogtebestand Nederland: digital terrain model of the Netherlands.
DGM	Digital Geological Model (of the shallow subsurface) is a layer model of geometry of geological Formations present in the Dutch Quaternary and Neogene. The geometry of each Formation is given as a top- and base surface and a thickness. The depth range of DGM is from the surface to approx. NAP-500 m. A description of DGM is included in Appendix E.
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 (stratigraphical) 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 included in Appendix D.
NL3D	Low resolution prequel of GeoTOP. NL3D is a 3D model of the subsurface containing voxels of 250 m x 250 m and 1 m depth. Each voxel contains lithological information only, but on a nation-wide scale. The depth range of NL3D is from the surface to NAP-50 m. NL3D is not available at DINOloket.
REGIS II	REgional Geohydrological Information System II is a hydrogeological addition to DGM. The subsurface is divided into sand and clay layers, corresponding to permeable and non-permeable layers. The model contains the geometry of these layers. In addition, for each unit the average hydrogeological parameters are given. The maximum depth of REGIS II is approx. NAP-500 m. A description of REGIS II is included in Appendix E.

Table 3.1, continued. Sources of subsurface information available for schematisation

Dataset	Short description
CPT	Cone Penetration Test, measuring cone 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).
Seismic CPT	Seismic Cone Penetration Test, performed with a seismic source at the surface and a cone containing geophones. While pushing the cone into the soil, at each given depth a seismic measurement is taken. In this way, both CPT and a seismic velocity profile (usually V_s) are obtained.
Paleogeographic maps	Maps showing the geographic evolution of the Netherlands from 5500 BC to present, Vos et al. (2011) and Vos et al. (2014).
Fault maps	Part of DGM, showing the locations of faults in the subsurface.
Salt dome maps	Part of DGM, showing the locations of salt domes
Buildings in Groningen field	Shapefile containing the locations of the buildings in the Groningen field.
V_{s30} maps	Maps showing V_{s30} values. Constructed by Arup (draft report, Villani and Neto, 2014)
V_p and V_s information from Shell	Logs of V_p and V_s are available in several boreholes in the Groningen field. These logs, however, start at 70 m below the surface and therefore do not provide information on the shallow part. Additionally, Shell is currently reprocessing the seismic reflection land surveys in order to derive information on V_s for the depth range between surface and approximately 120 m. At the moment of schematisation, this information was not yet available.

The versions and cut-off dates of data used in the schematisation of version 1 of the GSG-model are stated in Appendix C.

3.2 Borehole records

The most important source of subsurface information consists of borehole records from the DINO database. This was input for GeoTOP, but the borehole descriptions are also used as such as background information in the schematisation. Deltares obtained an official version of the DINO database on 2 September 2014. The locations of the DINO borehole records are shown in Figure 3.1. In total, there are now 19082 borehole records in the area of interest (Groningen field +5 km buffer). The maximum depth of the borehole records, however, varies greatly. This is visualised using colours in Figure 3.1.

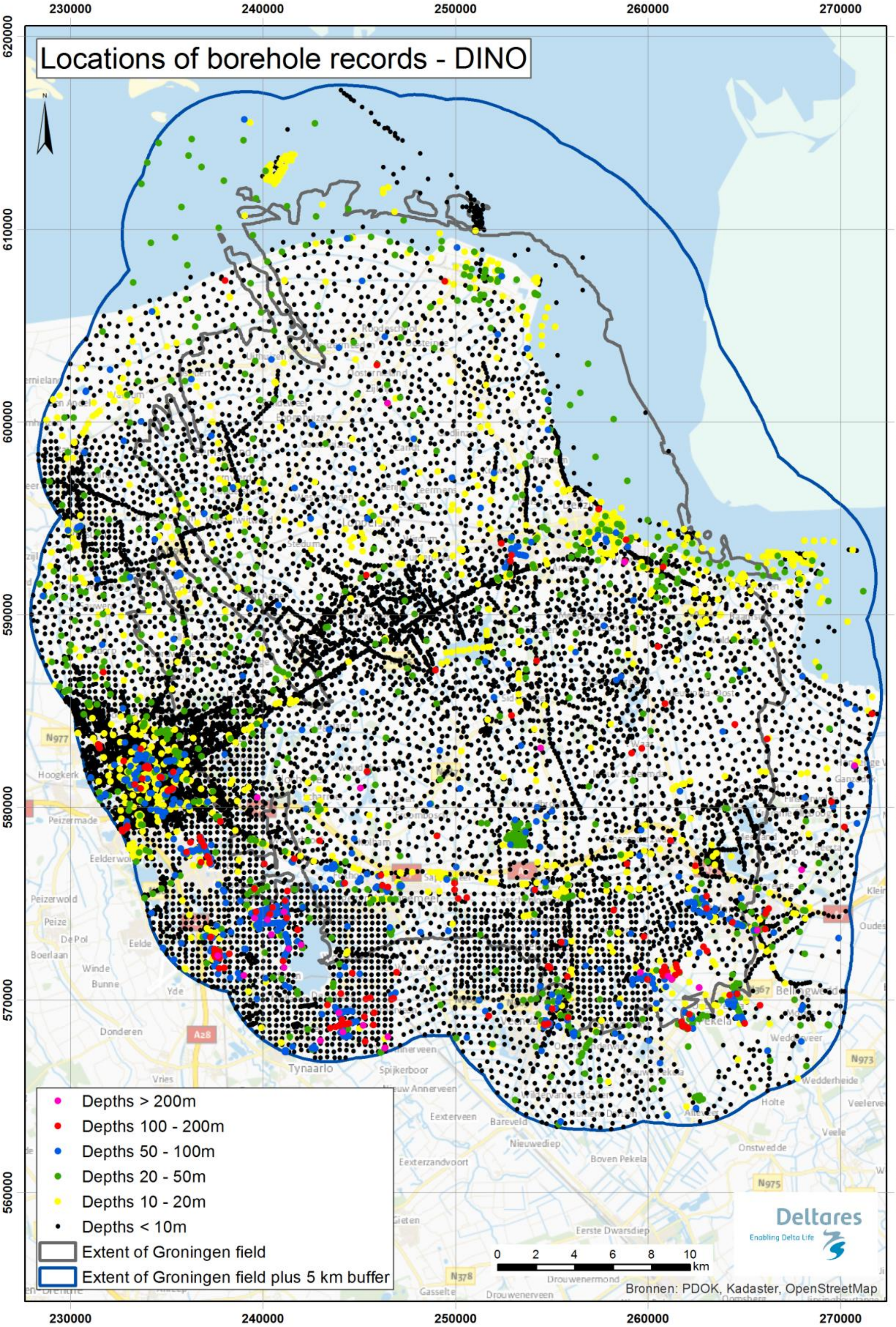

Figure 3.1 Location and depths of DINO boreholes records used for schematisation (source: DINO database 2 September 2014). Colours indicate the end depths of the boreholes. Visualisation of borehole density for various depth ranges is shown in Figure 6.9 and the figures in Appendix P.

3.3 CPT records

Another source of subsurface information consists of CPTs. The overview of all available CPTs is shown in Figure 3.2. Visualisation of borehole and CPT density for various depth ranges is shown in Figure 6.10 and the figures in Appendix Q. The depth distribution is shown in Figure 3.3.

During the course of the schematisation (September - November 2014), new information became available at several occasions. The database used for schematisation was updated accordingly. This means that data density varied during schematisation. An example is the delivery of more than 2000 CPTs by Fugro. They became available in two batches around 6 and 24 October 2014 and were incorporated into our database. Part of the schematisation was performed without these CPTs and part was performed with them. This is visualised in Figure 3.4. The CPTs of Wiertsema en partners were delivered on 17 November 2014. The schematisation was finished on 14 November 2014, so in the geological area map presented in this report (chapter 6) the Wiertsema en partners CPTs were not used.

Not all CPTs delivered by Fugro and Wiertsema en Partners could be included in the database (Rockworks). For the Fugro CPTs, approx. 100-200 could not be imported due to error messages and missing coordinates. For the Wiertsema en Partners CPTs, approx. 700 files in “gef” format were delivered. 557 of them were incorporated in the Rockworks database. Not all “gef” files actually contained CPTs. Additionally, error messages for several “gef” files and several double locations resulted in reduction of the number of CPTs included in the database. The total number of CPTs now included in the database is 5674.

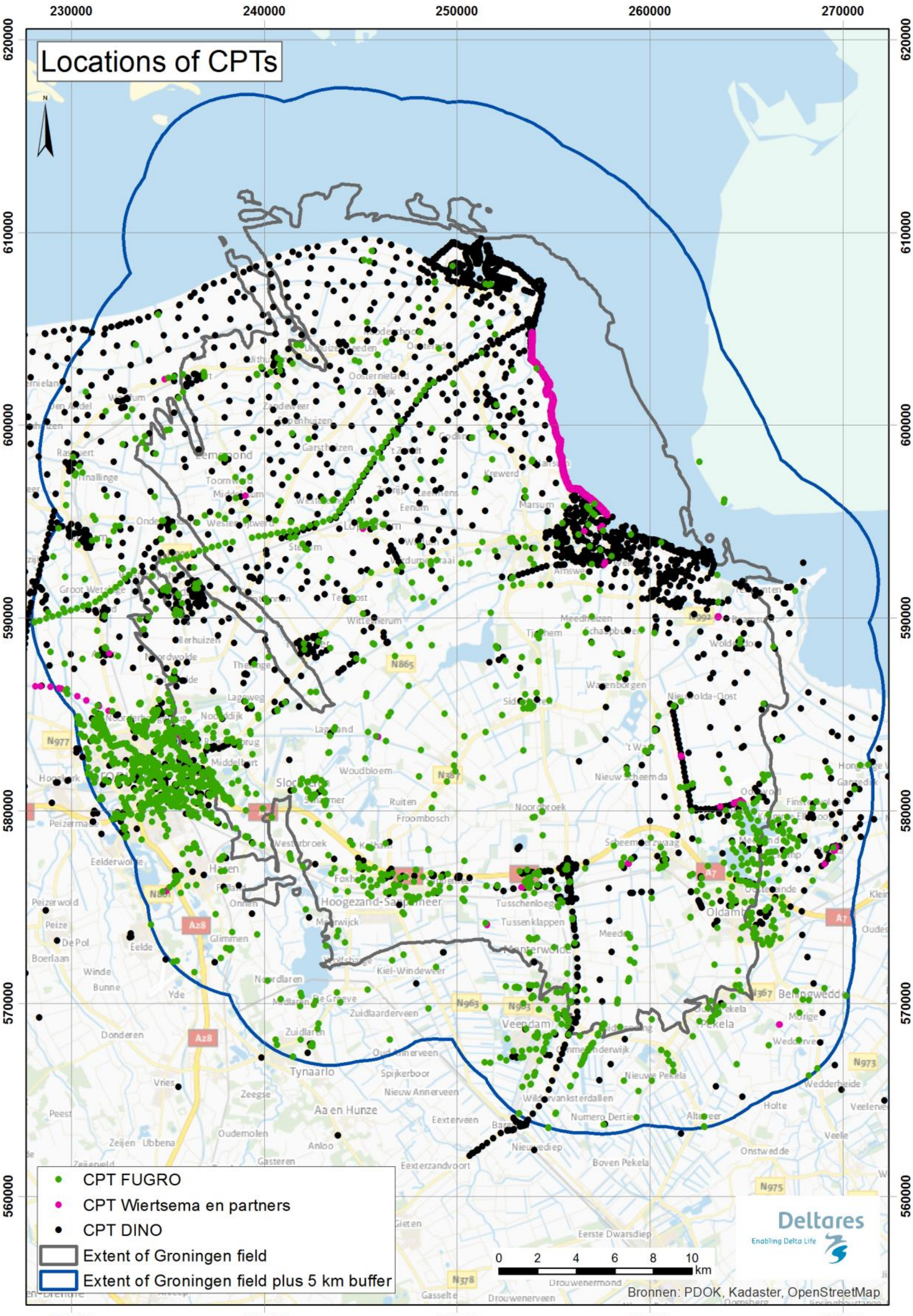

Figure 3.2 Location and source of available CPTs (17 November 2014). See also Figure 3.4 for the availability of CPTs during the schematisation process.

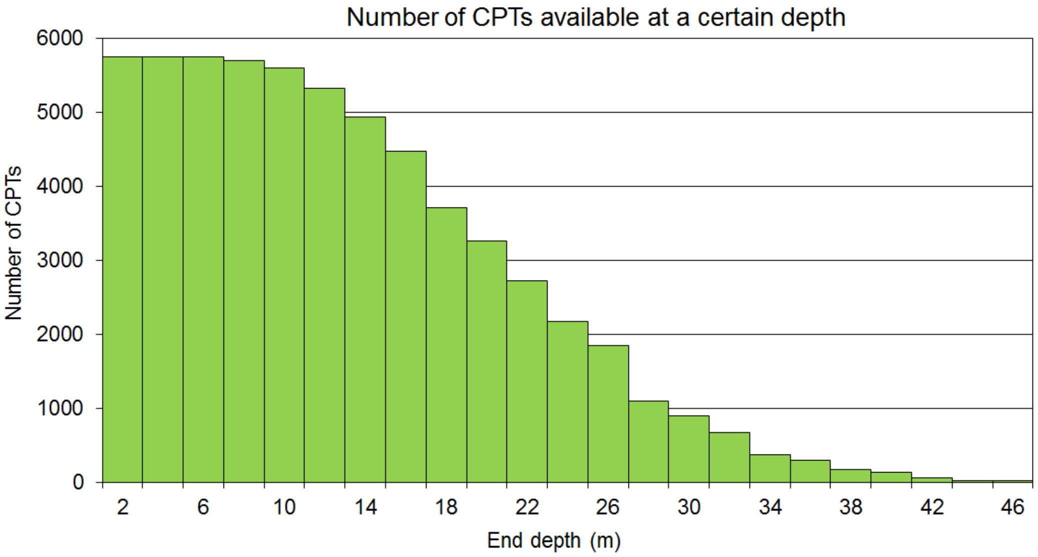

Figure 3.3 Number of CPTs available a certain depth for the full CPT database (17 November 2014). Interval range 2 m. In this figure, the cumulative number of CTPs is shown. For example, all CPTs with maximum depth of e.g. 8 m are also available for all higher situated depth ranges (in this case not only for 6-8 m, but also for 0-2 m, 2-4 m and 4-6 m).

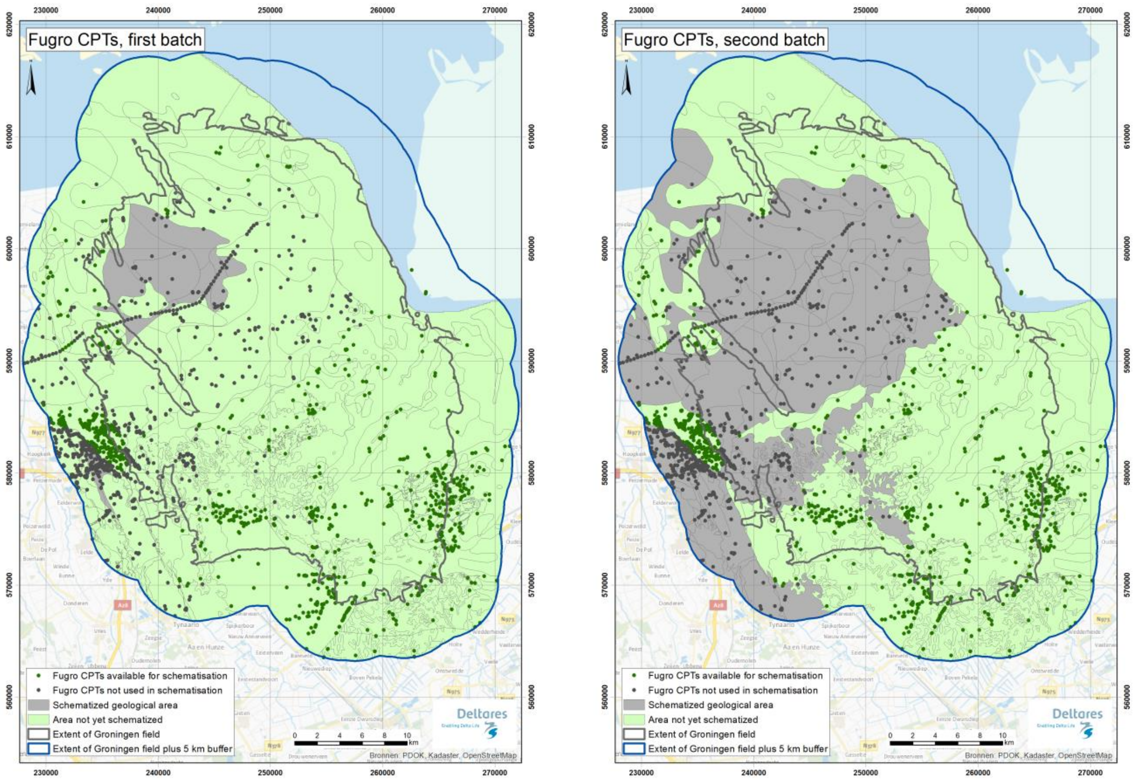

Figure 3.4 Availability of Fugro CPT for schematisation purposes. The grey areas were already schematised at the date of CPT delivery (left: first batch on 6 October 2014; right: second batch on 24 October 2014). Therefore, additional CPTs (grey dots) were not included in the schematisation. The green area had not been schematised at the date of CPT delivery. Therefore, the green dots of additional CPTs could be included into information used for schematisation purposes. Left panel: situation on 6 October 2014 (1st batch of Fugro CPTs available). Right panel: situation on 24 October 2014 (all of Fugro CPTs available).

3.4 Seismic CPT records

For the parameterisation of V_s, a dataset of Seismic CPTs (SCPTs) was used. This dataset consists of 61 SCPTs obtained from Deltares, Wiertsema en partners and Fugro. Generally, the maximum depth of SCPT is 30 m. The spatial distribution of SCPTs is shown in Figure 3.5.

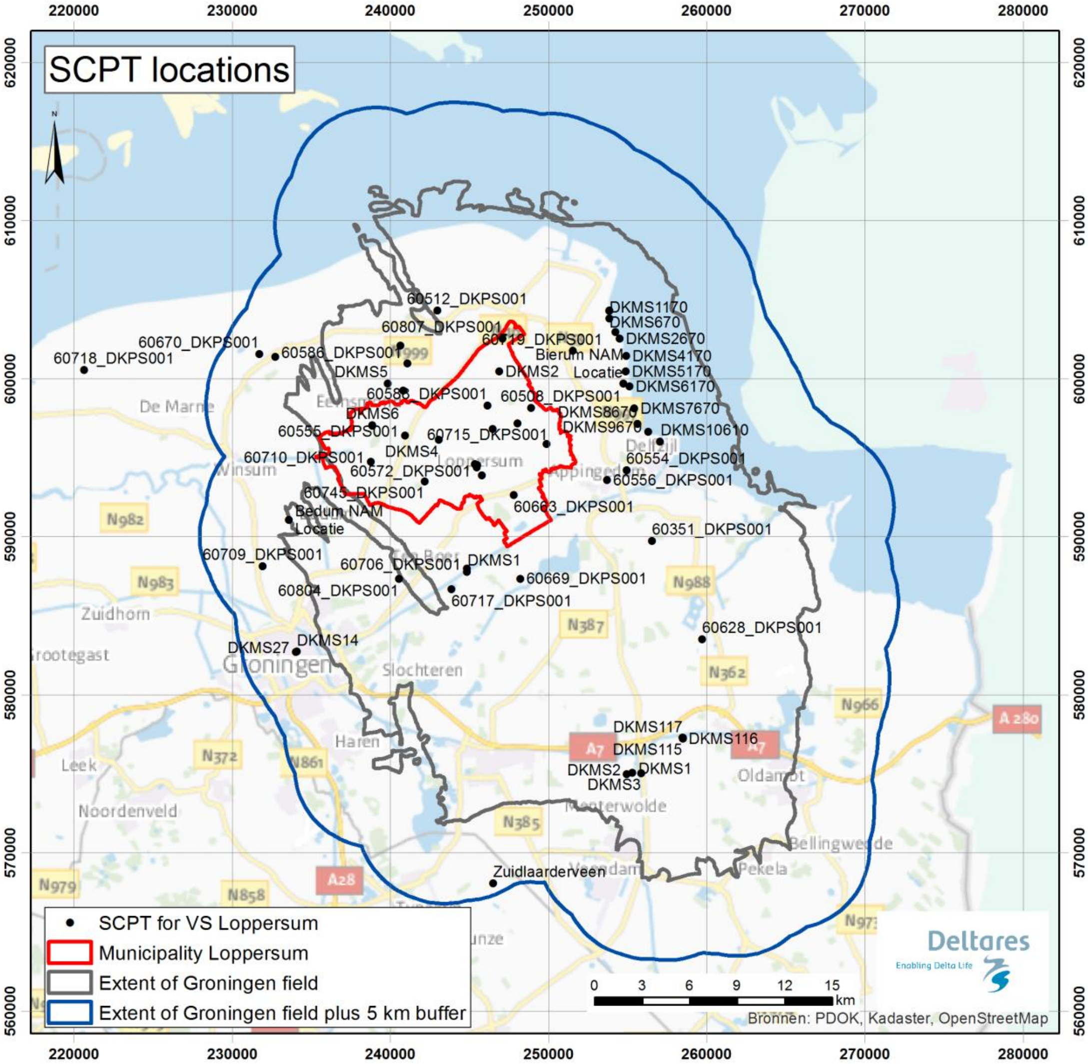

Figure 3.5 Location and source of available SCPTs (16 October 2014).

3.5 GeoTOP

3.5.1 General description of GeoTOP

GeoTOP is the latest generation of 3D subsurface models produced at 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 lithostratigraphical information, lithological class information (including grain-size classes for sand) and the probability of occurrence for each of the lithological classes.

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 is still under construction. A general description of GeoTOP Oostelijke Wadden and how the model is constructed is provided in Appendix D.

3.5.2 Beta version of GeoTOP

This study uses an unpublished beta-release of the GeoTOP “Oostelijke Wadden” model. It is important to note that this beta-release has not passed a thorough Quality Control. Some quality issues of the model are already known and, if relevant to the application at hand, described in section 3.5.3. The first round of Quality Control resulted in a number of issues that have been categorized into 8 groups. These 8 categories are described in section 3.5.4.

After the first quarter of 2015, a second version of the model will be compiled in which the GeoTOP QC issues will be addressed. This second version will pass through a second round of QC, which will lead to a third version of the model etc., until all issues are either resolved or considered not relevant.

In general, TNO emphasizes that there will be significant differences between the beta-version used in this study and the final version which will be published in 2015. The most important issues are discussed in the following section.

3.5.3 GeoTOP issues with respect to the application of site response

Several characteristics and quality issues of the model are relevant to the application for site response analysis.

Peat occurrence
The spatial distribution of peat that occurs at or near land surface (the brown voxels in Figure D.1 in Appendix D) is based on:
(a) Borehole descriptions from the DINO database maintained by TNO Geological Survey of the Netherlands.
(b) The soil map created by the national soil agency Alterra.

Collection of the boreholes and the soil mapping took place in the 1960s. Since then, large areas of the peat have disappeared due to drainage and subsequent oxidation. Alterra is currently working on an update of the peat occurrence in their map products (de Vries et al., 2013). This update, however, was only partially available when the beta-version of GeoTOP was constructed. The use of old data in the mapping of the peat distribution implies that the model overestimates the occurrence of peat at or near land surface. Soil-response calculations based on GeoTOP might therefore overestimate the site response, because site response is sensitive to peat occurrences.

Mapping of dwelling mounds ("wierden")
The Groningen area contains numerous historical dwelling mounds (or locally known as "wierden") which were built as refuge in times of flooding. These mounds were not mapped separately, but in an indirect way as part of a general mapping effort of anthropogenic deposits. Anthropogenic deposits are represented as grey voxels in Figure D.3 in Appendix D.

Anthropogenic deposits in GeoTOP "Oostelijke Wadden" were initially mapped using the general method applied to all GeoTOP modelling areas (Stafleu et al., 2012, p. 56 – 57). Additional mapping of anthropogenic deposits was carried out in part of Groningen that is covered by Holocene deposits. It is in this area (indicated by green colours in Figure D.1 in Appendix D) that the dwelling mounds occur. First, potential anthropogenic deposits were identified by a combination of two basic GIS operations:

(a) A selection of areas with an altitude of at least NAP+1.5 m (a rough indication of maximum flood levels).
(b) A selection of areas with a height difference of more than 1.5 m with the surrounding terrain.

Both these selected areas were subsequently inspected visually using aerial photographs and topographical maps and classified as either anthropogenic or natural deposits. During this visual inspection also other artificial-looking areas that were too shallow for the previous procedure were classified as anthropogenic deposits.

The way in which the anthropogenic deposits were mapped by TNO potentially leads to an underestimation of the number of dwelling mounds. For instance, dwelling mounds with an altitude of less than 1.5 m will not be recognized by used the procedure. In addition, it is not possible to distinguish the physical properties of dwelling mounds from those of other anthropogenic deposits.

Additional information on dwelling mounds might be found in the Archis database (http://archeologieinnederland.nl/bronnen-en-kaarten/archis). This database, however, is not publicly accessible.

Lithological composition of the Peelo Formation
The Peelo Formation is characterised by a very complex lithological infill. In general, three types of deposits are observed:

(a) Very stiff impermeable clay (potclay or "potklei'' in Dutch).
(b) Fine grained sand with a low permeability
(c) Sands with a high permeability.

The 3D spatial distribution of these sediments is highly variable and hence difficult to model due to a relatively low data density, especially at larger depths. Therefore, the V_s maps and STRATA-soil-types profiles in areas where sediments of the Peelo Formation occur should be used with caution.

Differentiating tidal deposits in the Naaldwijk Formation
In large parts of the Netherlands, the tidal deposits of the Naaldwijk Formation can be separated in an upper and a lower unit, the Walcheren and Wormer Members respectively.

The two members are usually clearly separated by the peat of the Nieuwkoop Formation, Hollandveen Member. In the northern part of the study area, however, the Hollandveen Member is absent and the two tidal members cannot be separated from each other. Therefore, the tidal deposits in this area are lumped in the Naaldwijk Formation, undifferentiated.

However, new work carried out after the release of the GeoTOP beta-version shows that the area where the two members can be distinguished is significantly larger than the extent of the Hollandveen Member. In the final version of the model, TNO will use the lithological contrast to separate the Walcheren and Wormer Members in a significantly larger area than in the beta-version. This separation will result in better constrained clay occurrences within the Naaldwijk Formation.

Data density
The most important data source of the GeoTOP model is DINO, the national Dutch subsurface database operated by TNO – Geological Survey of the Netherlands. At the moment of construction of the GeoTOP model, this database contained about 425,000 boreholes situated within the onshore part of the Netherlands, of which 42,722 are within the “Oostelijke Wadden” area (‘onshore’ includes the Wadden Sea). All borehole descriptions are stored in a uniform coding system (SBB5.1; Bosch, 2000). The largest part of borehole data consists of manually drilled auger holes collected by the Geological Survey during the 1:50,000 geological mapping campaigns. Most of the other borehole data comes from external parties like groundwater companies and municipalities. Because of the large share of manually drilled boreholes, borehole density decreases rapidly with depth (Figure 3.6). This implies that in general, model uncertainty increases with depth. The spatial distributions of boreholes with end depths used for the Oostelijke Wadden GeoTOP model are shown in Figure D.6 to Figure D.9 in Appendix D.

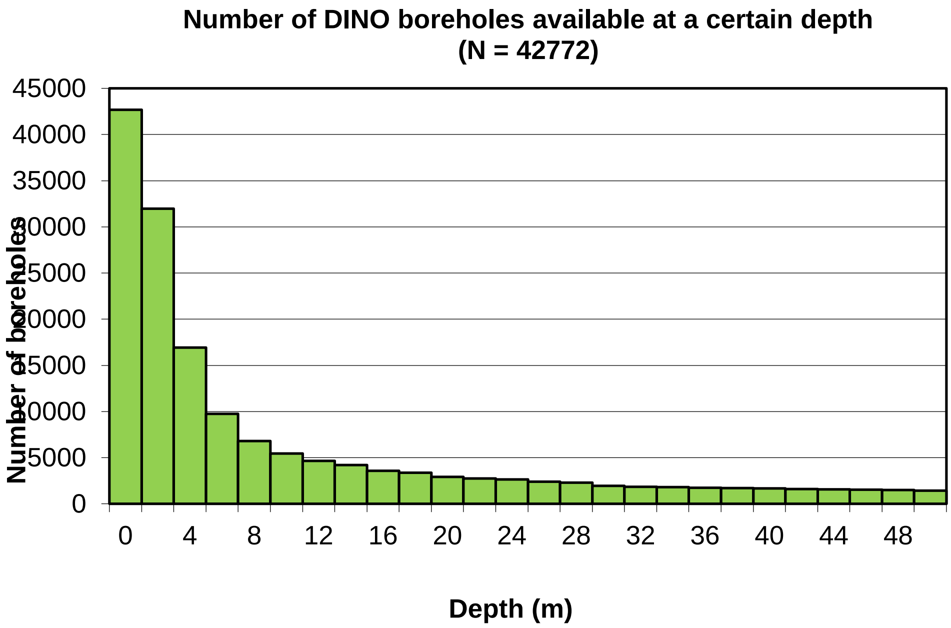

Figure 3.6 Number of DINO boreholes available a certain depth. N = 42,772; interval range 2 m. In this figure, the cumulative number of boreholes is shown. For example, all borehole records with maximum depth of e.g. 8 m are also available for all lower depth ranges (in this case not only for 6-8 m, but also for 0-2 m, 2-4 m and 4-6 m).

3.5.4 Findings of the first round of GeoTOP Quality Control (TNO)

The first round of Quality Control performed on the beta version of GeoTOP by TNO Geological Survey of the Netherlands resulted in several issues that have been categorized into 8 groups. The 8 categories and their impact on the GSG-model for Groningen for site response are summarized in Table 3.2.

Table 3.2 Issues of the first round of Quality Control of the beta-release of GeoTOP by TNO Geological Survey of the Netherlands.

Category	Number of issues	Expected impact on the GSG-model of Groningen for site response
Mapping of the maximum extent of the stratigraphical units in the model	47	High These issues have an effect on the occurrence of peat in the model.
Missing data-points in the modelling of the unit DRGI (glacial till)	11	High The glacial till is expected to have a large effect on the site response.
The modelling procedure sometimes results in a virtual erosion of thin layers. This issue will have to be solved by introducing a minimum thickness of these thin units.	4	High Thin layers of peat may be missing in the model.
Issues in the automatic stratigraphic interpretation of borehole descriptions, in particular the correct labelling of brook valley deposits	13	Medium Impact is limited to the brook valleys.
Integration of the DGM (Digital Geological Model) in GeoTOP	12	Medium The most important problems occur in the Waddenzee area which is not of interest in this study.
Geostatistical settings such as correlation distances, a-priori probabilities of occurrence and other parameters.	8	Medium These parameters will mainly affect the distribution of lithological classes within the Pleistocene units.
Data-quality issues in borehole descriptions, such as implausible land surface heights, low quality descriptions, outliers	9	Low These issues have a local effect only.
Issues concerning the modelling of coastal deposits on the Wadden Islands	4	None The Wadden Islands are not of interest in this study.

3.6 Sources used for the schematisation for two depth ranges

3.6.1 For surface to NAP-50 m depth range

The list below shows the complete set of data used for the shallow schematisation (surface to NAP-50 m):

- AHN
- Borehole records DINO.
- CPT records DINO.
- Fugro CPT when available (section 3.3).
- Beta version GeoTOP Oostelijke Wadden.
- Digital Geological Model (DGM), including fault maps.
- REgionaal Geohydrologisch InformatieSysteem (REGIS II).
- Paleogeographic maps.

Information on versions is included in Appendix C.

3.6.2 For NAP-50 m to NAP-200 m depth range

The list below shows the complete set of data used for the deep schematisation (approx. NAP-50 m to NAP-200 m):

- Digital Geological Model (DGM), including fault maps and salt dome maps in the Northern Netherlands.
- REgionaal Geohydrologisch InformatieSysteem (REGIS II).
- Borehole records extending to a depth of NAP-30 m or more, often accompanied by geophysical well logs. Only public data is used, available in the DINO database maintained by TNO Geological Survey of the Netherlands. Geophysical well logs available from wells used in the construction of the DGM v2.2 model were occasionally used when judged necessary.
- Additionally, geophysical well logs were used that were measured by Deltares in wells drilled for the purpose of installation of 200 m deep vertical seismic arrays. At the time of schematisation, only 15 raw data (not interpreted) logs were available. No updates of the deep schematisation were performed when new data became available.

Information on versions is included in Appendix C.

3.7 Visualisation

For visualisation purposes, three programs were used: iMod, Rockworks and ArcGIS. iMod is 3D visualisation software developed at Deltares and is used to draw profiles through the 3D compilation of all data layers. An example of an iMod view is shown in Figure 3.7. ArcGIS is used to view borehole locations, superimposed on the available map views (e.g. AHN, paleogeography) and to adjust polygons of geological areas. The Rockworks functionality partly overlaps the iMod functionality. Additionally, Rockworks allows the development of a database and performs better in visualising profiles of CPT logs.

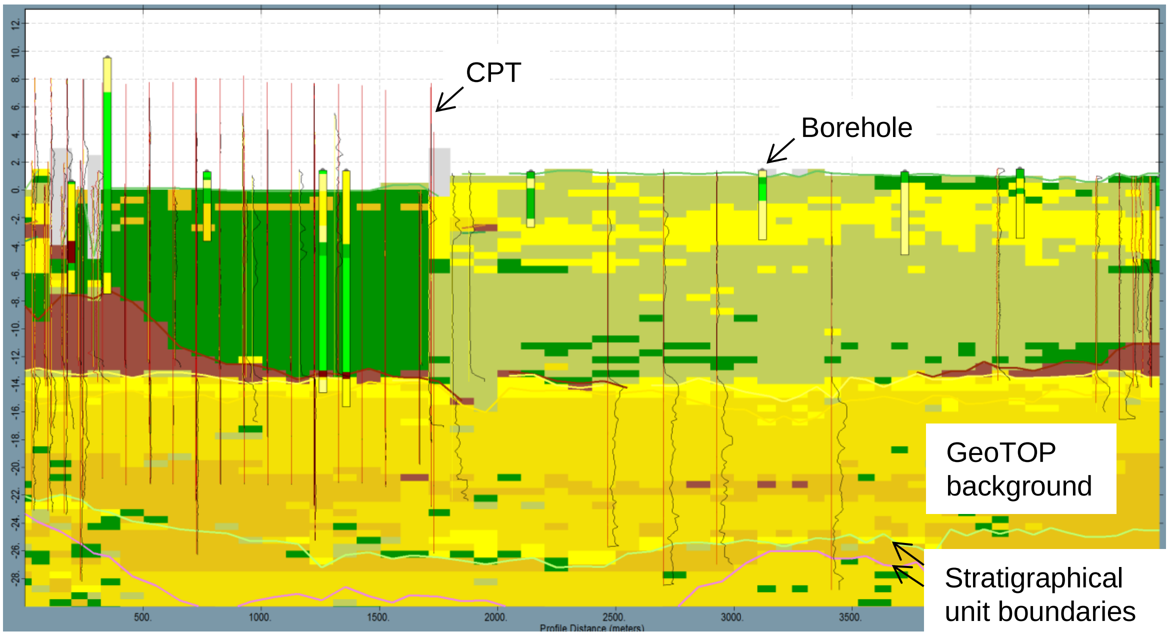

Figure 3.7 Example of iMod view for a cross section in Groningen, showing borehole records, CPTs, GeoTOP background and boundaries of stratigraphical units.

3.8 Caveats and future work

Regarding sources of information, we identified the following caveats:

- There is low data density below NAP-30 m (Figure 3.1 and Figure 6.9). This means that the reliability of the GSG-model below this depth range decreases.
- Especially in the deeper parts of the GeoTOP model, the automatic lithology assignment procedure may end up with no data for the voxel. In that case, the lithological infill is randomly drawn from the lithological proportions for that lithostratigraphical unit. This might lead to an unrealistic succession of clay and sand layers in the GeoTOP voxel stack.
- The GSG-model is based on the beta version of GeoTOP. We expect that differences between the beta version and the official release of GeoTOP will necessitate adjustments of the version 1 of the GSG-model.
- The database of background information is growing continually. The impact of adding new subsurface data to the database needs to be assessed. New information for the depths larger than 30 m is generally very valuable and potentially improves the GSG-model. New information comes from planned and future geophysical and geotechnical fieldwork campaigns, work in progress by NAM, Deltares and others.

For the next version of the GSG-model and derived products such as V_{s30} maps and site response calculations, we anticipate the following future developments regarding sources of information:

- The official release of GeoTOP.
- Including additional sources of information that were not included in version 1 of the GSG-model, such as:
  - 70 borehole logs (multitool and sonic) to 200 m depth at vertical seismic array locations.
  - SCPTs and Vs information at 18 KNMI accelerograph stations and vertical seismic array locations.

- Information from deep wells (70 m to 3 km depth) from NAM.
- Assessment of need to include results from the update on peat occurrence by Alterra.
- Any other relevant information provided by third parties.

4 Method of schematisation

4.1 Background of schematisation

The calculation of the site response to ground shaking by earthquakes will be performed on vertical subsurface profiles generated by the GSG-model for Groningen (+5 km buffer) presented in this report. By clustering the outcomes of site response for vertical subsurface profiles among distinct areas with a typical geological build-up, probability distributions of the site amplification effect for these distinct areas can be made. This chapter describes the method by which the representative vertical subsurface profiles were determined and how the distinct geological areas for clustering were mapped. The definition of a geological area and a profile type is provided in the box below.

Definitions
Profile type: *characteristic sequence of deposits*

Example of profile type
Nawa-niho-nawo-niba: contains the succession (from top to bottom, young to old) of the Formation of ***Na****aldwijk –* ***Wa****lcheren Member (marine deposits), Formation of* ***Ni****euwkoop –* ***Ho****lland peat Member (terrestrial organic deposits), Formation of* ***Na****aldwijk –* ***Wo****rmer Member (marine deposits), Formation of* ***Ni****euwkoop –* ***Ba****sal peat Member (terrestrial organic deposits).*

Geological area: *area with distinct mappable geological build-up, expressed by one or several profile types. The aim is to account for all potential sequences occurring within this area. Therefore, a geological area can either be homogeneous and contain one main profile type or heterogeneous containing several profile types. The mappability depends on the quality and distribution of subsurface information and associated uncertainties in actual composition.*

For the Groningen field, the site amplification effect will be calculated taking into account the variability in the subsurface. Since the subsurface is heterogeneous and the exact vertical subsurface profile at any specific location between boreholes cannot be determined with certainty, a stochastic approach is preferred which accounts for the most probable vertical subsurface profile present at a site.

Deltares has acquired experience with probabilistic approaches for schematising the heterogeneous subsurface below dikes in various projects (e.g. WTI approach, Hijma and Kruse, 2014; Hijma et al., 2015). Based on the probabilistic approach for dikes and the availability of GeoTOP, the extension to 3D has been developed. The workflow is included in section 4.3.

4.2 Criteria and level of detail in schematisation

The level of detail required for the subsurface model is determined by the sensitivity of the site response calculations to the distribution of lithologies with respect to depth and thickness.

Site response calculations were performed using the program STRATA. This software performs one-dimension linear-elastic and equivalent-linear (SHAKE type) site response analyses using time series or random vibration theory ground motions (Kottke et al., 2013). STRATA allows for stochastic variation of the site properties, including the shear modulus reduction and material damping curves, shear-wave velocity, layering, and depth to baserock. One of the inputs of STRATA is the soil-type profile: a vertical succession of layers with a soil-type and a shear-wave velocity attached to them. In STRATA, the term ‘soil’ is used for unconsolidated sediments. In this study, we characterise the ‘soil’ by the lithological composition of geological units (lithostratigraphy) derived from the geological subsurface model.

To investigate the sensitivity of site response for the Groningen field, two preliminary sensitivity studies of site response were performed prior to schematisation and construction of the Groningen subsurface model. The two sensitivity studies for site response were:

1. Indicative site response calculations for typical profile types to be found in Groningen. Goal: to obtain first indications of Groningen site response. Results in Appendix F.
2. Sensitivity analysis of site response for amplification sensitive soil types, i.e. various thicknesses and depths of peat and/or clay. Goal: to determine the level of detail needed in the Groningen subsurface model. Results in Appendix G.

The first sensitivity study (Appendix F) shows that nearly all considered profiles typical for Groningen show an increase in Peak Ground Acceleration (PGA) at the surface for increasing peak acceleration at baserock. All cases show a decrease in Amplification factor (which is the ratio between PGA at the surface and at baserock) for increasing peak acceleration at baserock. For low accelerations at base level, the variation in PGA at the surface is limited. For increasing peak accelerations at baserock, the differences in site response increase. Nearly all profiles suggest that there is a limit to the maximum PGA at surface. Depending on the soil layering this limit is between 0.2g and 0.5g (for an input signal of 0.1g).

The results of the second sensitivity study (Appendix G) are summarised as follows:

- In general, the effect of varying thickness and/or lithology on the soil factor decreases with depth. This means that variations in e.g. stiffness contrasts are more important in the shallow subsurface (e.g. a peat layer at 2 m depth) than in the deeper subsurface (the same peat layer at 8 m depth).
- The effect of a large contrast in soil properties on amplification varies monotonic with thickness of the layers involved: the amplification factor is generally lower for a thicker layer of low stiffness.
- A notable effect of the thickness of surface layers on site amplification (high, up to 3x) is found for thin softer surface layers. This effect decreases with depth. For thin soft layers deeper than 5 m below the surface the effect is minimal.

With the results of the sensitivity studies in mind, we formulated requirements concerning the detail in vertical build-up (Table 4.1 and Table 4.2). These are summarized as follows:

- Layers less than 1 m thickness are neglected, with exception for peat and very soft clay layers with a top at less than 7 m below surface level. The minimum thickness is 0.5 m for peat and very soft clay.

- Thin peat layers at shallow depth have an effect on the site response. Therefore, for the incorporation of peat and soft clay layers of 0.2 to 0.5 m thickness at less than 7 m below surface level, an equivalent layer must be defined. This is in order to include the properties of those soft thin layers while avoiding an overall decrease in layer thicknesses (and corresponding increase in number of layers). This equivalent layer of 1 m thickness contains the properties of both the thin peat and the other lithology that is present in this 1 m (i.e. organic clay types).
- In the upper 5 m the thickness variation of peat and clay layers are to be schematised in classes with steps of 0.5 m.
- Between 5 and 10 m below surface level, the layer thickness and the depth of stiffness contrasts such as peat/clay, peat/sand, soft clay/clay, clay/sand, are to be represented in classes with a variation of 1 m.
- Below 10 m below surface level, thickness and depth of large stiffness contrasts are to be represented in classes with a variation of about 2 m.
- Below 30 m below surface level, thickness and depth of large stiffness contrasts are to be represented in classes with a variation of about 5 m. This variation can be larger at greater depth, depending on the availability of borehole data.

Table 4.1 Level of detail needed for depth and thickness specification of subsurface units in scenarios. Note: the variation "±" applies to the modal range of depth and thickness variation, since depth and thickness of most subsurface units are not normally distributed.

Depth below surface level (m)		**Depth variation boundary, ± (m)**	**Thickness variation, ± (m)**	
From	**to**			
0	5	1	0.5	peat, clay
			1	other lithology
5	10	1	1	
10	30	2	2	
> 30		> 5	> 5	

Table 4.2 Adaptation of thin layers of peat or very soft clay in the depth range of 0 to 7 m below the surface. Very thin layers are neglected, and for moderately thin layers an equivalent layer is assumed for the 0.5 or 1 m thickness (see Table 4.1).

Thickness (m)		
From	**To**	**How to handle**
0	0.2	not represented
0.2	0.5	equivalent layer
0.5	1	1 m layer assumed

4.3 Workflow of schematisation

Due to the maximum depth of NAP-50m of the GeoTOP model, the GSG-model is divided into two depth intervals:

- Surface to NAP-50 m (limit of GeoTOP).
- Approx. NAP-50 m to NAP-200 m or to the base of the Peelo Formation when it is deeper than NAP-200 m (maximum of NAP-235 m).

The workflow for schematisation is based on geological areas, GeoTOP voxel stacks and depth scenarios (Figure 4.1). The blue parts have been performed so far. The depth of the reference baserock horizon has not yet been defined. Therefore, the shallow (0-50 m below surface) and deeper part (> 50 m below surface) of the model are not yet combined. The combination will be performed in a later stage. The entire workflow including the determination of site response will be tested for the municipality of Loppersum pilot.

The description of work for constructing a geological subsurface model is provided in Figure 4.1. The following sections give descriptions of the steps performed so far, shown in blue in Figure 4.1.

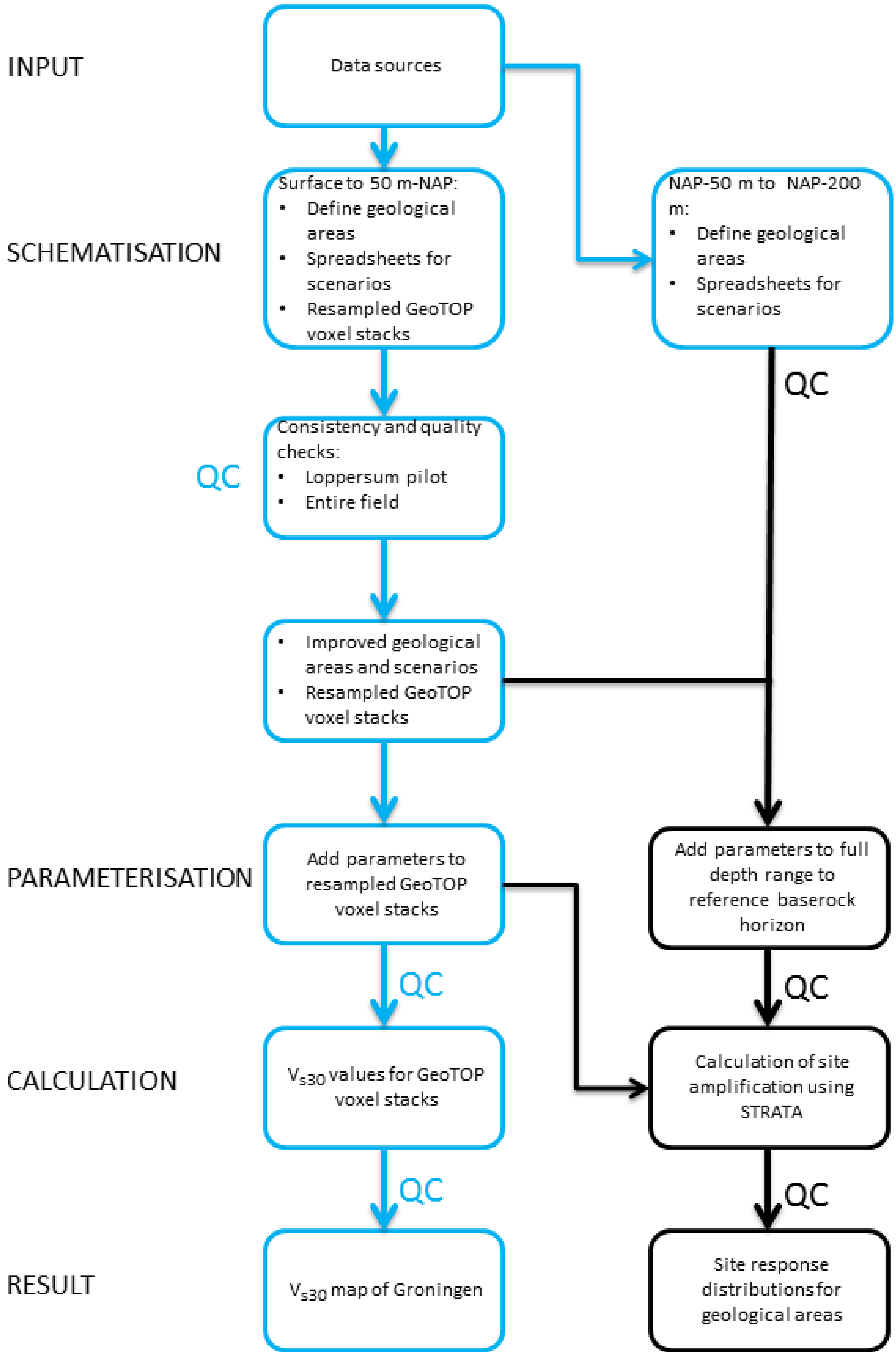

Figure 4.1 Workflow for geological schematisation of the shallow subsurface of the Groningen field. QC = Quality control. The items in blue have been performed so far. The items in black are future work.

4.4 Surface to NAP-50 m depth range

4.4.1 Draft subdivision into geological areas

The schematisation aims to map unique areas with a typical lithological succession or a combination of lithological successions, and to define scenarios with typical lithological successions for these areas. The areas are later used to cluster site response model calculation output which results in a distribution of site amplification effect at a given location.

The lithologies are represented by relevant mappable lithofacies. A lithofacies is a subdivision of any stratigraphic unit that has characteristic lithological features and is related to a certain type of sedimentary environment. Relevancy in this case means that each unit shows typical geomechanical behaviour. The geomechanical behaviour is the result of contrasts in stiffness of the subsurface (site amplification effect) or liquefiable sands (liquefaction potential).

To construct the first order map of geological areas (draft subdivision), the extent of relevant stratigraphic units (shapefile layers) that likely play a role in site effect and that have distinctive patterns were identified. These stratigraphic units are summarised in Table 4.3 and reach to approx. NAP-20 m. It is expected that e.g. peat has a profound effect on site response. Examples of the extent of stratigraphic units such as the Naaldwijk Formation, Holland Peat and Basal Peat are shown in Figure 2.6. Not all Formations that are present in the area of interest are included in Table 4.3. The eolian cover sands of the Boxtel Formation (Wierden Member), for example, cover almost the entire area of interest. Therefore, they cannot be used to distinguish between geological areas and are not included in the analysis to construct the first draft of the geological area map.

Table 4.3 Relevant geological stratigraphic units (Formations) for the Groningen schematisation for the shallow subsurface (up to approx. NAP-20 m) for the purpose of constructing the draft subdivision into geological areas.

Formation and member	Deposits (age)	Abbreviation
Naaldwijk Formation Walcheren member	Tidal deposits (Holocene)	nawa
Nieuwkoop Formation Holland peat member	Peat (Holocene)	niho
Naaldwijk Formation Wormer member	Tidal deposits (Holocene)	nawo
Nieuwkoop Formation basal peat member	Peat (Holocene)	niba
Nieuwkoop Formation Griendtsveen peat Member	Peat (Holocene)	nigr
Nieuwkoop Formation Nijbeets peat member	Peat (Holocene)	ninb
Boxtel Formation Singraven member	Stream deposits (Holocene)	bxsi
Eem Formation	Estuarine/marine/tidal deposits (Pleistocene)	ee
Drenthe Formation Gieten member	glacial till (Pleistocene)	drgi

Short descriptions of the relevant Formations are provided (in Dutch in Appendix H).

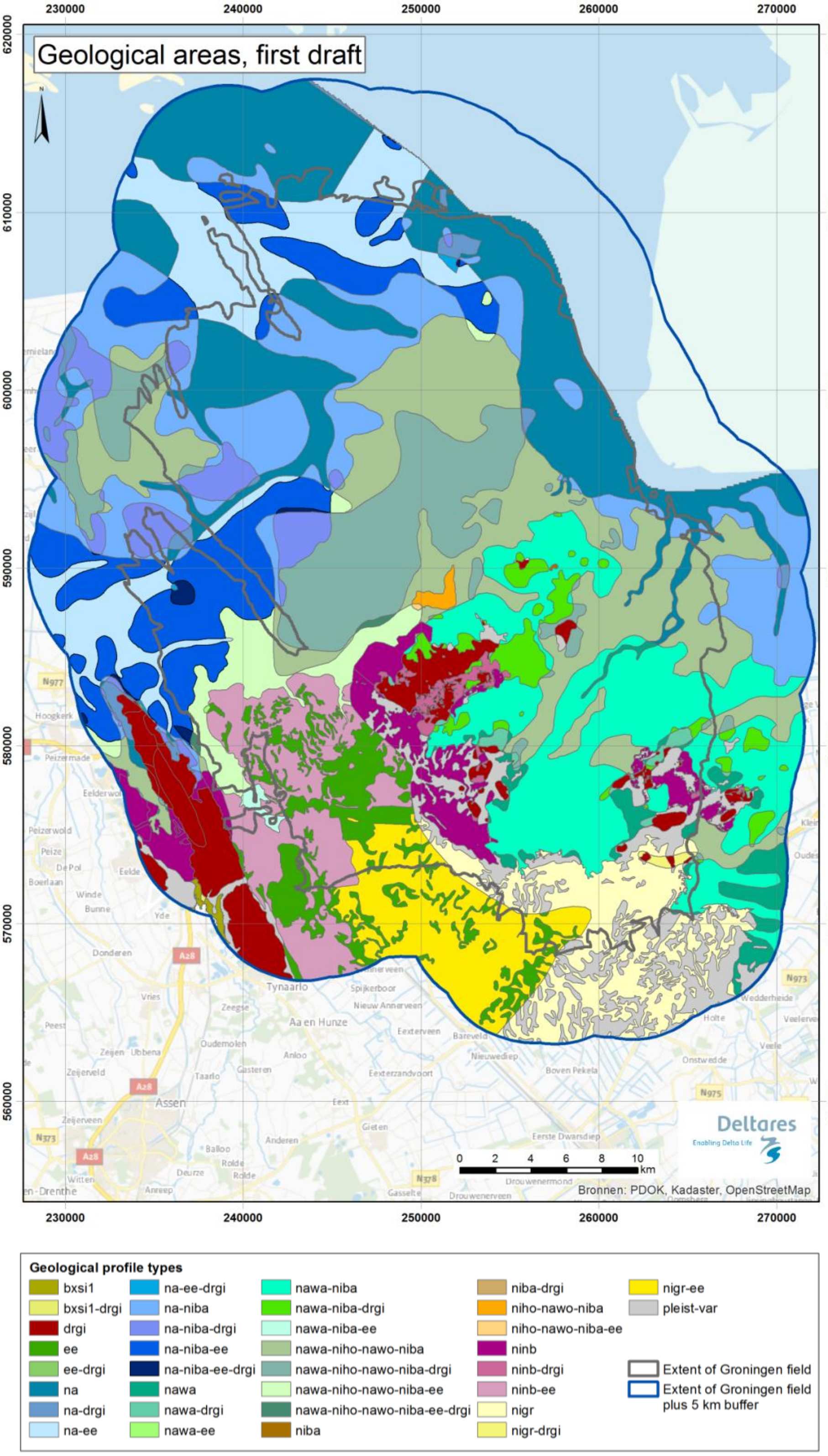

Figure 4.2 First draft of geological areas in the area of interest (Groningen field + 5 km buffer), based on the polygons containing the extents of the Formations of Table 4.3. Similar colours denote areas with similar stratigraphical build up. Legend shows geological profile types that are based on actual stratigraphy. For abbreviations, see Table 4.3.

Next, the distribution of these layers (x-y extent) was visualised using the extent shapefiles from GeoTOP. Hence, the entire area of interest was automatically subdivided into first order polygons determined by typical successions (profile types) of relevant geological formations as described above. The lateral distribution of these geological formations is determined on the basis of their presence in boreholes and represents the maximal potential distribution of occurrence. Figure 4.2 shows the subdivision of the area in first-order polygons, representing the first draft of geological areas.

4.4.2 Geological areas: boundary refinement and scenario definition

The outlines of the automatically determined first order polygons were adjusted on the basis of more detailed mapping of the distribution of stratigraphical units (Formations) and lithofacies using all available subsurface data (see chapter 3). Also, the polygons are subdivided on the basis of the probability of occurrence or changes in depth of the geological layers. The boundaries of the sub-areas can for instance be based on mappable boundaries of trends in depth or thickness of peat or soft clay. Small areas may be aggregated or removed if they are not mappable. This refinement is driven by expert knowledge of geologists and is performed manually. The mapping of boundaries is aided by lithology query maps (example in Figure 4.3), representing the result of queries on the borehole database. For instance the depth and/or thickness of critical layers can be visualised on a colour scale. Figure 4.3 shows the bottom of peat in all available boreholes. The colour code indicates the depth in m below the surface. There is a gradient from north to south: in the north the bottom of the peat layers is present at larger depths than in the south. Patterns in query maps on various attributes of borehole records aid in refining the locations of the boundary of the geological areas.

The adjustment of the outlines of the geological areas is determined by drawing profiles in iMOD and Rockworks, and representations of depth information of borehole records in ArcGIS to provide a geographical overview. In this stage, the GeoTOP, DGM and fault maps for example will serve as a background for the borehole information and will be used to confirm or reject the chosen boundary or to relocate it. To check the full extent of the geological area, various cross sections are drawn.

The identified vertical subsurface profiles (scenarios) within a polygon are entered in a spreadsheet. These scenarios are more detailed than the profile types from the draft subdivision (Figure 4.2), because they contain information on depth, thickness and probability of occurrence of the layers in the scenario. Moreover, the main profile type area (e.g. 21 = nawa-niho-nawo-niba-drgi) is subdivided into geological areas 2101, 2102 etc. based on differences in the scenarios. In the spreadsheet, the scenarios are visualised in graphs (example see Figure 4.4). Remarks can be entered, describing special features and the justification of boundaries.

At the end of this procedure, all initial first-order polygons have an adjusted outline, are recombined or divided into more polygons with a higher level of detail. For each polygon scenarios are defined. This allows the possibility of a cross-check with the GeoTOP output for the same polygon and makes the decisions for the schematisation traceable. The consistency and quality check for the Loppersum pilot is described in section 5.2.

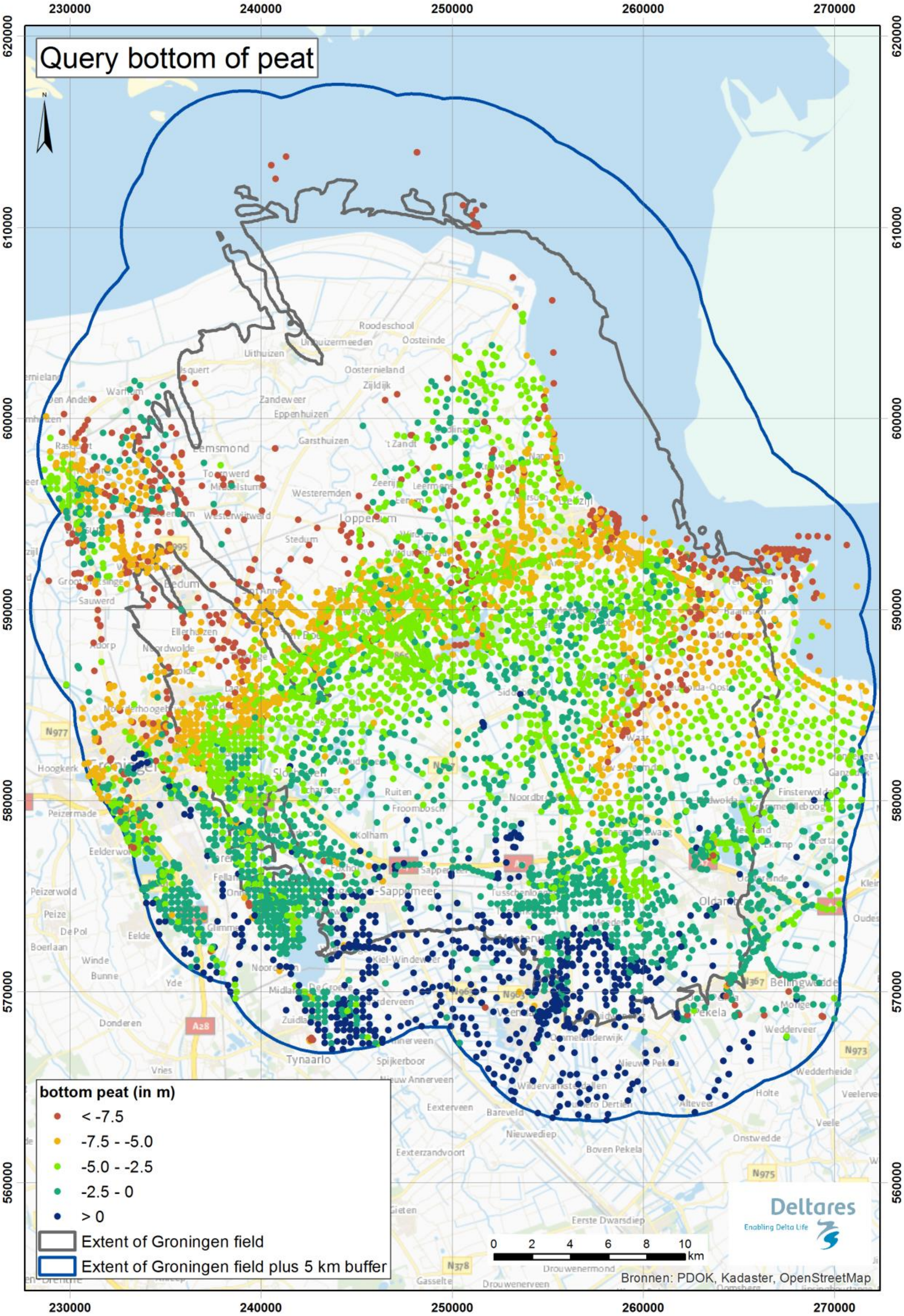

Figure 4.3 Example of a "dot map" in which the bottom of peat is indicated for all boreholes. This map is generated in GIS by a query on the borehole descriptions. Numerous "dot maps" can be generated by selecting different attributes from the borehole records.

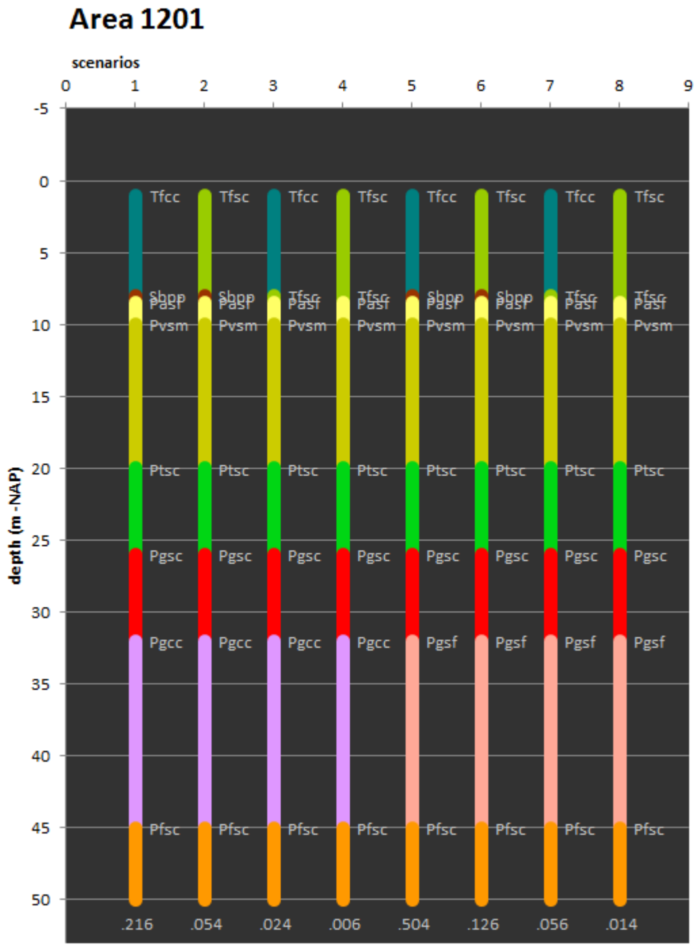

Figure 4.4 Example of visualisation of scenarios for geological area 1201 (for location, see Figure 6.1). The number ***12**<u>01</u> denotes that the basic profile type in this area is of type* ***12*** *(na-niba-ee, see legend of Figure 6.2); <u>01</u> is a serial number. Several lithofacies are present in only part of the scenarios, e.g. scenarios 1, 3, 5 and 7 contain Tfcc (mudflat with clay), whereas scenarios 2, 4, 6 and 8 contain Tfsc (mudflat channels with alternating clay and sand) in the top. In this example, all scenarios contain Pgsc (fluvioglacial course gravelly sand) at approx. NAP-26 to 32 m.*

4.4.3 Specific use of GeoTOP for the GSG-model

A general description of GeoTOP is provided in Appendix D. For the schematisation, voxel stacks of the beta version of GeoTOP Oostelijke Wadden are used. A voxel-stack is a vertical sequence of voxels at a particular (x,y)-location. Voxel-stack analysis can be used to create customised 2D raster maps for a wide range of applications (example in Figure 4.5).

In case of GeoTOP, two operations are applied to the voxel stacks to prepare them for site response calculations:

1. Resampling of voxel stacks (described in this section 4.4.3).
2. Assignment of V_s values to the layers (section 4.6)

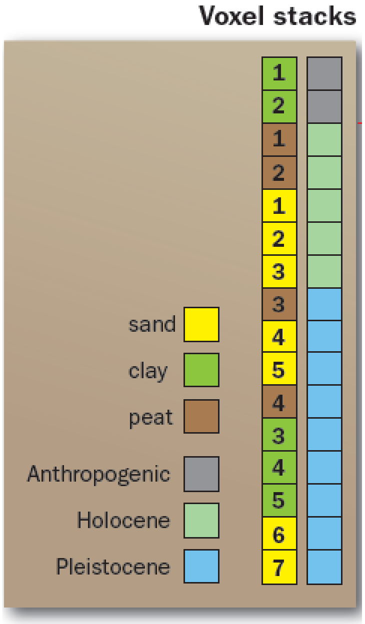

Figure 4.5 Example of input for voxel stack analysis. Left column shows a voxel stack of most likely lithological class and right column shows the lithostratigraphical unit. Together, they can be used to create customised 2D raster maps. Adapted from: Dambrink et al. (2014). In this study, the lithological classes are more extensive than just peat, clay and sand, see Table 4.6.

The voxel-stacks were resampled in order to meet the requirements of a soil profile in STRATA. This has been performed for the Loppersum pilot. The requirements are linked to the level of detail needed in schematisation (section 4.2). The processing steps for resampling include:

1. Classify the lithological classes of GeoTOP according to Table 4.6.
2. Aggregation of voxel of 0.5 m thickness into layers with a thickness of 1 m. In order to do so, we systematically examined the two voxels within every meter and selected *at random* one of the voxels. Random selection is favoured over other selection criteria in order to avoid any bias in the result.
3. Merging of successive voxels of equal lithostratigraphical unit and lithological class into one soil-type layer.

Figure 4.6 shows an example of the reclassification and aggregation of a voxel stack near Loppersum. The reclassified and aggregated voxels of Figure 4.6 are merged in step 3 into a soil-type profile (Table 4.7). The attributes in the soil profile are defined in Table 4.8.

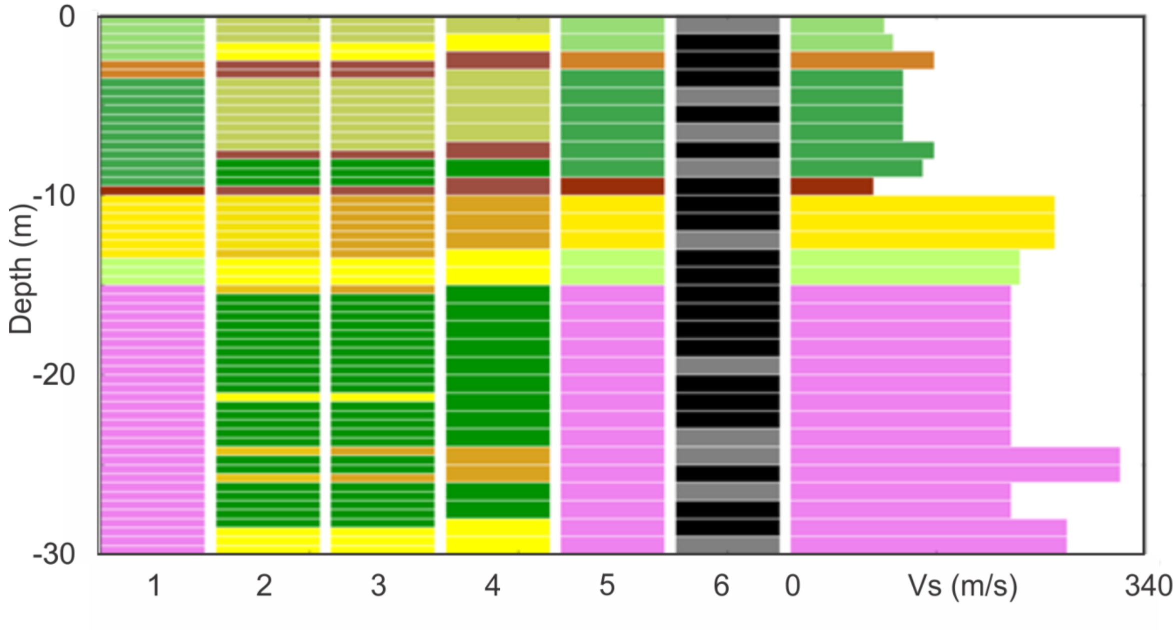

Figure 4.6 Example of voxel aggregation for a voxel-stack near Loppersum. From left to right: (1) original GeoTOP lithostratigraphical units (for colours see Table 4.4); (2) original GeoTOP lithological classes (for colours see Table 4.5); (3) reclassification of lithological classes; (4) aggregation of reclassified lithological classes into voxels of 1 m thickness; (5) aggregation of lithostratigraphical units into voxels of 1 m thickness; (6) the random selector used to select the upper or lower voxel (grey: select upper voxel; black: select lower voxel); Far right: bar graph of the shear-wave velocity assigned to the voxels.

Table 4.4 Codes and colours for lithostratigraphical units in GeoTOP. Abbreviations for Formations in Table 4.3.

Code	Description
Anthropogenic deposits	
AAOP	Anthropogenic deposits
Naaldwijk Formation	
NASC	Naaldwijk Formation, Schoorl Member
NAZA	Naaldwijk Formation, Zandvoort Member
NA	Naaldwijk Formation, no differentiation between Wormer and Walcheren Members
NAWA	Naaldwijk Formation, Walcheren Member
NAWO	Naaldwijk Formation, Wormer Member
Nieuwkoop Formation	
NINB	Nieuwkoop Formation, Nij Beets Member
NIHO	Nieuwkoop Formation, Hollandveen Member
NIBA	Nieuwkoop Formation, Basal Peat Bed
Boxtel Formation	
BX	Boxtel Formation
BXKO	Boxtel Formation, Kootwijk Member
BXSI1	Boxtel Formation, Singraven Member, upper unit
BXWI	Boxtel Formation, Wierden Member
BXSI2	Boxtel Formation, Singraven Member, lower unit
Other units	
EE	Eem Formation
DR	Drente Formation
DRGI	Drente Formation, Gieten Member
DN	Drachten Formation
URTY	Urk Formation, Tynje Member
PE	Peelo Formation
UR	Urk Formation, Tynje Member
ST	Sterksel Formation
AP	Appelscha Formation
PZWA	Peize and Waalre Formations (Peize in this area)

Table 4.5 Codes and colours for lithological classes in GeoTOP

Anthropogenic	Fine sand
Clay	Medium sand
Clayey sand	Coarse sand
Peat	

Table 4.6 Lithological classes in the GeoTOP “Oostelijke Wadden” model and in this study. Adjusted from Table D.2 in Appendix D.

Lithological class used in GeoTOP	Grain size	Lithological class used in this study
Anthropogenic deposits	N/A	Anthropogenic deposits
Organic deposits (peat)	N/A	Organic deposits (peat)
Clay	N/A	Clay
Clayey sand and sandy clay	N/A	Clayey sand and sandy clay
Fine sand	63 – 150 µm	Fine sand
Medium sand	150 – 300 µm	Medium sand, coarse sand, gravel and shells
Coarse sand, gravel and shells	> 300 µm	

Table 4.7 Example of a soil profile based on the voxel-stack in Figure 4.6. The soil profile is input for the site response calculation in Strata. The bottom of the model is formed by a half-space starting at 30 m depth. For abbreviations of Formations see Table 4.3.

Number (X_Y)	Depth below land surface (m)	Thickness (m)	Soil type (combination of lithostratigraphical unit and lithological class)	Shear-wave velocity V_s (m/s)
245450_593850	0	1	NAWA_Clayey sand and sandy clay	158
245450_593850	1	1	NAWA_Fine sand	206
245450_593850	2	1	NIHO_Organic deposits (peat)	50
245450_593850	3	4	NAWO_Clayey sand and sandy clay	158
245450_593850	7	1	NAWO_Organic deposits (peat)	85
245450_593850	8	1	NAWO_Clay	114
245450_593850	9	1	NIBA_Organic deposits (peat)	100
245450_593850	10	3	BX_Medium and coarser sand	290
245450_593850	13	2	EE_Fine sand	257
245450_593850	15	9	PE_Clay	225
245450_593850	24	2	PE_Medium and coarser sand	330
245450_593850	26	2	PE_Clay	225
245450_593850	28	2	PE_Fine sand	286
245450_593850	30	Half-Space	Baserock	294

Table 4.8 Attributes of a soil profile based on the voxel-stack in Figure 4.6 and Table 4.7.

Attribute	Explanation
Location	Unique identification number of the voxel-stack, composed by the (x,y) location of the voxel midpoints.
Depth	Depth of the top of the layer in m below land surface. In all profiles, the top of the first layer is at 0 m below land surface.
Thickness	Thickness of the layer in m. In all profiles, the last layer has a thickness value “half-space”.
Stratigraphy	Code of the lithostratigraphical unit of the layer (not shown in the example in Table 4.7).
Lithology	Lithological class of the layer (not shown in the example in Table 4.7).
Soil_Type	Soil-type of the layer, composed by its lithostratigraphical code and its lithological class. In all profiles, the last layer has a soil-type value of the “Baserock”, which is the top of the elastic half-space in STRATA.
V_s	Shear-wave velocity of the layer in m/s.

4.5 NAP-50 m to NAP-200 m depth range

The deeper subsurface of the area of interest (Groningen gas field +5 km buffer) was schematised and subdivided using a different method than the surface to NAP-50 m part. The difference is due to the lack of coverage by the GeoTOP model (maximum extent to NAP-50 m) and the far lower data-density. The maximum depth in the GSG-model is the base of the Peelo Formation.

At the start of the schematisation process, the deeper schematisation was aimed at the interval between NAP-50 m and NAP-200 m. During the schematisation process, however, the depth range was adjusted both to deeper and to shallower depth ranges. The shallower depth ranges were covered to take into account the interval between the top and base of the Peelo Formation. In some areas this led to an extension upward to NAP-5 to -15 m (instead of NAP-50 m). The extension in the shallow domain ensured an overlap between the shallow and deep schematisations and prevented units crossing the NAP-50 m boundary from being neglected or overlooked. The overlap facilitates the establishment of the connection between the two models of the different depth ranges at a later stage in the project. In several other cases, the model was extended deeper than NAP-200 m, in the case that the base of the Peelo Formation reaches deeper (maximum of NAP-235 m).

Following the criteria established for the shallow subsurface (section 4.2), beds with a thickness smaller than 5 meters were not schematised. Occasionally, their presence was noted in the stochastic scenarios. The composition was derived from the available wells combined with the geometries of the REGIS II v2.1 model. Occasionally, the described intervals in a well contradict the interpreted clayey (low permeable) beds interpreted in REGIS II. Either more detailed lithological properties (clayey or loamy beds or pebbles) or geophysical well logs may justify this interpretation.

The level of detail of the schematisation in the deeper subsurface (> NAP-50 m) suffers from a lower data density compared to the shallow subsurface. The available boreholes are sometimes clustered, often related to pumping stations for groundwater extraction. Additionally, the quality of the borehole descriptions is sometimes rather poor which affects the quality of the schematisation of the subsurface.

A slightly different approach than for the shallow part was used to correctly schematise the deep subsurface and designate geological areas. Two successive steps were performed:

1. Initially, the area of interest was subdivided into uniform areas based on the geometries and composition of the DGM v2.2 (with the fault maps associated with this model) and REGIS II v2.1. From the deepest unit (Breda Formation) to the shallowest lithostratigraphic unit (Peelo Formation), the presence (including a rough indication of their thickness) or absence of the geological units and their low permeable hydrogeological components was used to construct this initial subdivision. The salt dome map was used as background information. This resulted in initial polygons of geological areas.
2. Subsequently, each initial polygon was examined with 2D profiles drawn in iMOD, comparable to the approach described for the shallow subsurface. In iMOD, the DGM v2.2 and REGIS II v2.1 models as well as the borehole data from DINO were visualised. Geophysical well logs were accessed by a link to the DINO database when expert judgement called for their additional information. In this assessment, discrepancies between the REGIS II v2.1 and the more recent DGM v2.2 were solved on the fly, generally by fitting REGIS II into the newer DGM model. Deeper hydrogeological units with low permeability were not mapped continuously in the REGIS II v2.1 model in the northern part of the research area. These were now interpreted and schematised based on the few wells present in the area and on geological expertise. Borehole information other than from the wells used to construct these models was directly incorporated in the scenarios. When a newly measured geophysical well log was available in a polygon it was interpreted and incorporated in the scenarios for that polygon.

The assessment of the individual polygons often led to changes in the geometrical extent of the initial polygons: several were merged, split or otherwise changed. The final polygons usually have one to four scenarios attributed to them. These scenarios may have large discrepancies compared to the models as a new interpretation was made based on all above mentioned input data.

The geological units are shown in their lithostratigraphic position in Table 4.9, with the associated facies codes and interpretation. In the “deep” schematisation, the geological units above the Peelo Formation were not schematised and are labelled as Aaop (in this case a dummy code).

Table 4.9 Geological units used in the deep schematisation (approx. NAP-50 m to NAP-200 m) with their respective facies units and the geological interpretation.

Geological unit	Facies code	Interpretation
Shallow units	Aaop	Dummy code: units grouped and not schematised in the deep scenarios.
Peelo Formation	Pgsf	Fluvioglacial outbreak sands, usually very fine to fine (<180 µm) but occasionally up to very coarse with some gravel (see notes in scenarios). May occasionally contain thin clay or loam beds.
	Pgcc	Potclay (Nieuwolda Member), generally thick and compact clays or alterations of clay, loam and very fine sand.
Appelscha Formation	Pfsc	Fluvial coarse sand and gravels. Often combined with the Peize Formation in the scenarios.
Peize Formation	Pfsc	Fluvial coarse sand and occasional gravels. Often combined with the Appelscha Formation in the scenarios.
	Pvbd	Heterogeneous fluvial sediments. Used in two intervals: a clay/loam bed present at the top of the Peize Formation (PZ-k-1 in REGIS II) and a thick complex unit in the lower part of the unit (Balk Member and/or PZ-c in REGIS II). This complex unit contains clay, loam and fine to very coarse sand.
Oosterhout Formation	Ntsc	Shallow marine sediments, mainly complex alterations of very fine sand, loam and clay. Occasional thin shell beds are present.
Breda Formation	Ntcc	Open marine sediments, mainly clay and loam with occasional fine glauconite rich sand.

4.6 Parameterisation - V_s

4.6.1 Background

For the development of location specific Ground Motion Prediction Equations (GMPEs), it is necessary to characterize the subsurface in terms of shear wave velocity distribution.

The V_{s30} method to determine the site effect was developed as a practical way to translate the variability of the shear wave velocity of soil layers into an amplification factor to be applied in GMPEs. In this method, the time-averaged shear wave velocity over the vertical depth interval between the surface and a depth of 30 m (V_{s30}) is used. Values of V_{s30} can be determined *in situ* by several means. At present, the commonly used method (in the Netherlands) is by performing a seismic cone penetration test (SCPT). This test produces shear wave velocities of predetermined test intervals (usually at a spacing of 1 m). The time-averaged V_s over 30 m can be calculated using V_s values versus depth.

V_{s30} observations are typically known at point locations. In order to obtain a V_{s30} map that covers the Groningen field (+5 km buffer), interpolation between the point observations is required. In an earlier version of a Groningen V_{s30} map, e.g. by Arup (Villani and Neto, 2014), the point observations were converted to a continuous grid by the kriging interpolation method. In that approach, however, variations in geology are not accounted for.

In this report, we use a different method to obtain V_{s30} values at locations where no measurements are available. Our approach takes into account the geology. This is done in two ways: first, by deriving Groningen-specific Vs relations for the Formations and lithology that are present in the region. Secondly, using the GSG-model to aggregate V_{s30} results to the level of geological areas.

4.6.2 Available data

The locations of SCPTs in the Groningen field + 5 km buffer are shown in Figure 4.7. The dataset consists of 61 SCPTs. 60 of them were used in the statistical V_s analysis. One SCPT was excluded from the statistical analysis, because of bad data quality. The general trends from this SCPT were considered in the expert judgement. The relatively large number of SCPTs enables the direct correlation between the shear wave velocity and geological units recognised in the area of interest.

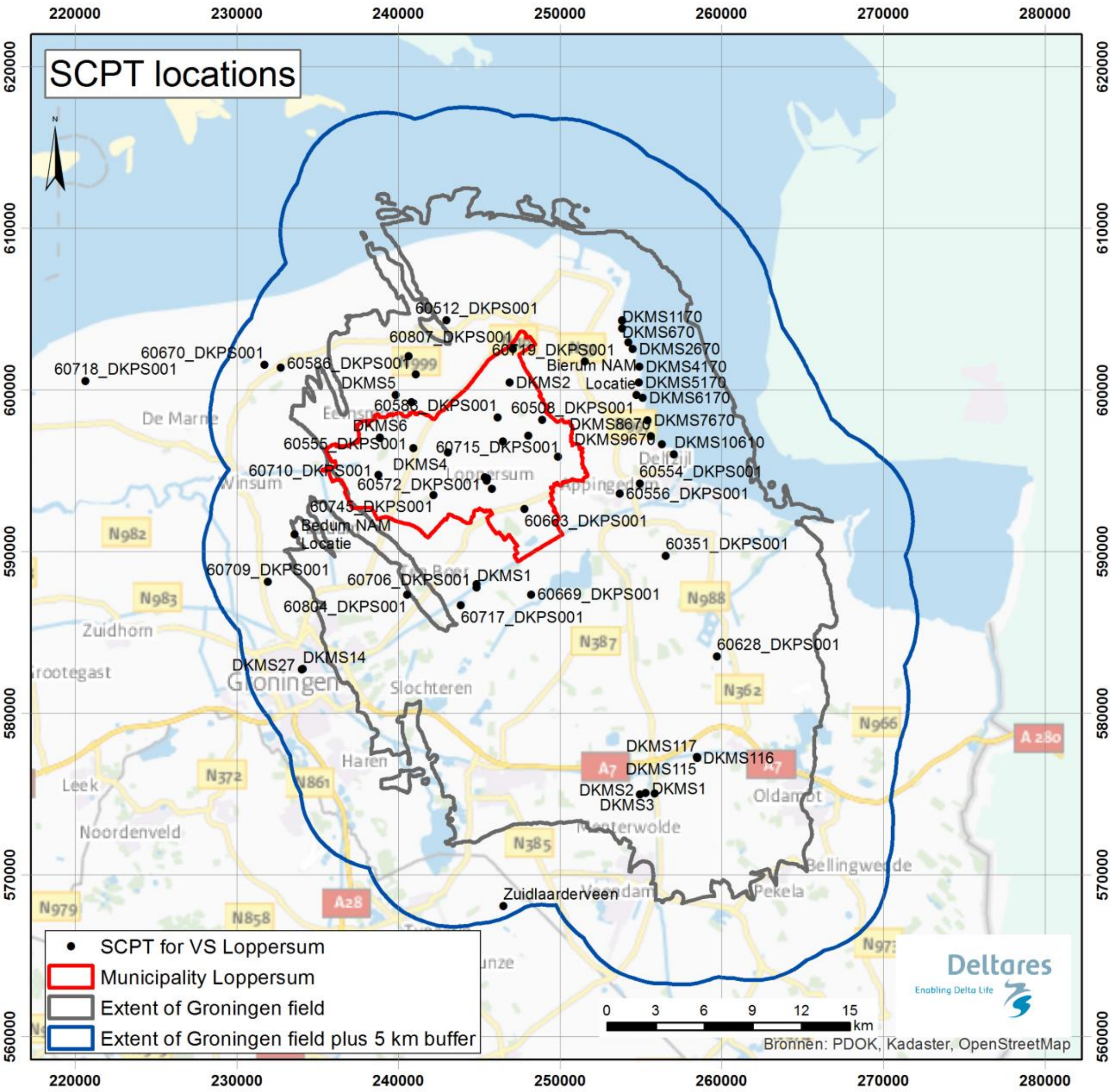

Figure 4.7 Locations of available of seismic cone penetration tests in the area of interest.

4.6.3 Method for improved look up table for V_s

In general, V_s depends on lithostratigraphy and lithology. Using literature values (e.g. Wassing et al., 2003), V_s values can be assigned to Formations and in some cases to lithological classes. The relatively large dataset of SCPTs available for the Groningen field, owing to recent site investigation campaigns, facilitates the improvement of the look-up tables and obtaining Groningen-specific V_s relations.

Apart from directly using SCPTs to derive V_s relations, another option is to use generic relations between cone resistance q_c from CPT and V_s (e.g. Andrus et al., 2007 and references therein). The large database of SCPTs and CPTs for Groningen offers an opportunity to derive Groningen-specific relations between q_c, V_s and lithology. This will be future work.

For the current analysis, we used the SCPT dataset of Groningen, consisting of 60 locations. In this dataset, variations in V_s values, lithostratigraphy and lithology are present. The idea behind the improved look up table for V_s is to derive representative values for V_s (average and standard deviation) taken from the SCPTs for all combinations of lithostratigraphy and lithological class present in the top 30 m of the area of interest. In this way, it is possible to assign different shear wave velocity values to the same lithological class in different Formations. For instance, fine sand in the Boxtel Formation has a lower shear wave velocity than fine sand in the Peelo Formation.

Although the SCPT dataset is relatively large (60 SCPTs), not all combinations of lithostratigraphy and lithological class are represented in the SCPTs. There are still data gaps for a number of units. For these units, we estimated the value for V_s based on Wassing et al. (2003) and expert judgement.

The three steps taken to construct an improved and Groningen-specific look up table for V_s are:

1. Interpretation of the SCPT dataset: assignment of lithostratigraphical units and lithological classes to the SCPTs.
2. Construction of histograms of V_s values for combinations of lithostratigraphy and lithological class that are represented by the SCPTs.
3. Construct a Groningen-specific look up table for V_s, using the statistics from step 2, Wassing et al. (2003) and expert judgement.

Step 1 Interpretation of the SCPT dataset
In the first step, a stratigraphical unit and a lithological class have been assigned to each of the measured V_s intervals in all 60 SCPTs. This was done manually by (engineering) geologists. The stratigraphical unit was determined based on the CPT results, supported by the GeoTOP model of lithostratigraphy. Manual handling was required in order to adjust stratigraphical boundaries in GeoTOP to boundaries observed in local (hence more detailed) CPT measurements.

Subsequently, a lithological class (corresponding to the lithological classes in GeoTOP, Table 4.6) was determined based on the CPT measurements of cone resistance and friction ratio. The automatically determined lithological class, based in the combination of the methods by Douglas and Olsen (1984) and Robertson (2009) served as an indication for lithological class. The relations between CPT parameters and classification are known to be site-specific and

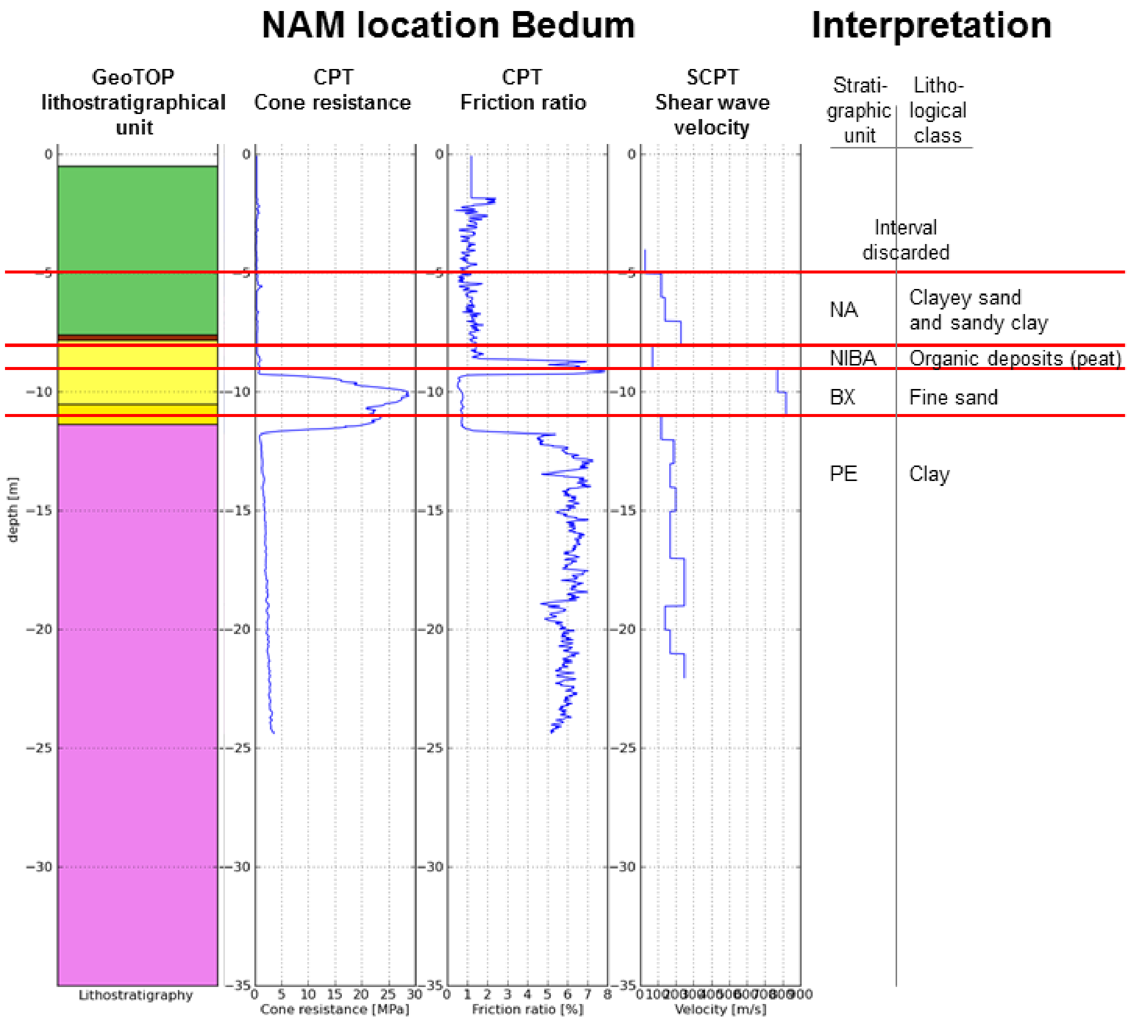

Figure 4.8 Example of interpretation of SCPTs, for the NAM location Bedum. From left to right: lithostratigraphical unit from the regional GeoTOP model, colours as in Table 4.4; CPT cone resistance; CPT friction ratio; V_s from SCPT at the same location as CPT; interpretation by Deltares in terms of lithostratigraphy and lithological class conforming to the units in GeoTOP. The horizontal red lines indicate the boundaries of the units, based on the SCPT record.

therefore automatic soil classification can only be regarded as indicative. The final lithological class was determined by expert judgement of lithology based on the CPT measurements.

The CPT and SCPT at the NAM location “Bedum” serves as an example (Figure 4.8). From the regional GeoTOP model, we expect a succession (top to bottom) of Naaldwijk Formation, Nieuwkoop Formation, Basal Peat Bed, Boxtel Formation, Wierden Member, Boxtel Formation undifferentiated and Peelo Formation. The cone resistance and friction ratio show that the top interval consists of clay from the Naaldwijk Formation (NA). The interval consisting of peat can also be recognized between 8.3 and 9.2 m depth. We interpreted this layer as Nieuwkoop Formation, Basal Peat Bed (NIBA). In the SCPT, the shear wave velocity is very low, consistent with peat values. The next interval, between 9.2 and 11.5 m depth, clearly consists of fine sand with high cone resistance and low friction ratio. These fine sands are interpreted as the Boxtel Formation (BO). In GeoTOP, two members of the Boxtel Formation were distinguished. However, these two members cannot be recognized separately in the CPT and SCPT. Therefore, the fine sands are regarded to be part of the

Boxtel Formation, undifferentiated. The bottom interval consists of clay from the Peelo Formation (PE).

All 60 SCPTs are interpreted in this way. During the interpretation, the following method has been used:

- V_s measurements from the unsaturated zone have been discarded.
- Extreme and outlier values for V_s have been discarded based on expert judgement.
- As a result of the difference in resolution between CPTs (measurement every 2 cm) and SCPTs (measurement every 1 m), the lithological boundaries observed in the CPTs will never perfectly align with recorded changes in V_s in the SCPTs. V_s values from intervals that are centred around a transition between two characteristically different lithologies have been discarded whenever these boundary effects cause values for V_s that are representative for neither lithology.
- Differentiation between different stratigraphical units of Pleistocene sands based on CPTs is problematic. Apart from the Boxtel Formation, Wierden Member (BXWI), which has a distinct shape in the CPT, and the Drenthe Formation, Schaarsbergen Member (DRSC), which may be distinguished based on its stratigraphical position, no distinction was made between stratigraphical units in Pleistocene sands. These have all been grouped under the Peelo Formation.
- Holocene peat layers from the Nieuwkoop Formation can often not be recognized in the CPTs. When present, the peat layers are generally thinner than the 1 m intervals of V_s. Hence, a reliable V_s value cannot be assigned to the peat layers at most sites. At some of the sites, the Naaldwijk Formation contains layers of organic clays which may be equivalent to peat layers of the Nieuwkoop Formation.
- It was not possible to distinguish differences in V_s value for the different Members of the Naaldwijk Formation. As a consequence, no distinction was made between Naaldwijk Formation, Walcheren Member and Naaldwijk Formation, Wormer Member: NAWA, NAWO and NA were all grouped into “NA”.
- It was not possible to distinguish specific V_s values for medium sands and coarser sands. The lithological classes of medium and coarser sands were therefore combined.

Step 2 Histograms of V_s and statistics

The SCPT analysis provided average values and standard deviations of V_s for the most common geological units in Groningen. Figure 4.9 shows examples from distributions of V_s values derived from SCPTs for the Naaldwijk Formation, for different lithological classes and for Nieuwkoop Basal Peat (organic/peat). For Naaldwijk clay (Figure 4.9, top left panel) and Naaldwijk sandy clay and clayey sand (Figure 4.9, top right panel), the number of observations is large, and the distributions are more or less Gaussian. For the fine sand (Figure 4.9, bottom left panel), the distribution seems to be bimodal. The Nieuwkoop Basal Peat set, consisting of peat (Figure 4.9, bottom right panel), shows that there are very few observations (7 in total). The average V_s is regarded as not representative for this unit, also because of the fact that the peat layers are often thinner than the 1 m V_s intervals in the SCPTs. In this case expert judgement overrules the statistical values.

All histograms for units represented in the SCPTs are included in Appendix I. About half of the histograms show more or less Gaussian distributions. In some cases, e.g. for the Drenthe Formation, the amounts of V_s observations (9 for each lithological class) is too small to check for a representative Gaussian distribution. Nonetheless, in the following analysis we assume that the distributions are Gaussian. The averages and standard deviations of the units represented in the SCPTs are given in Table 4.10.

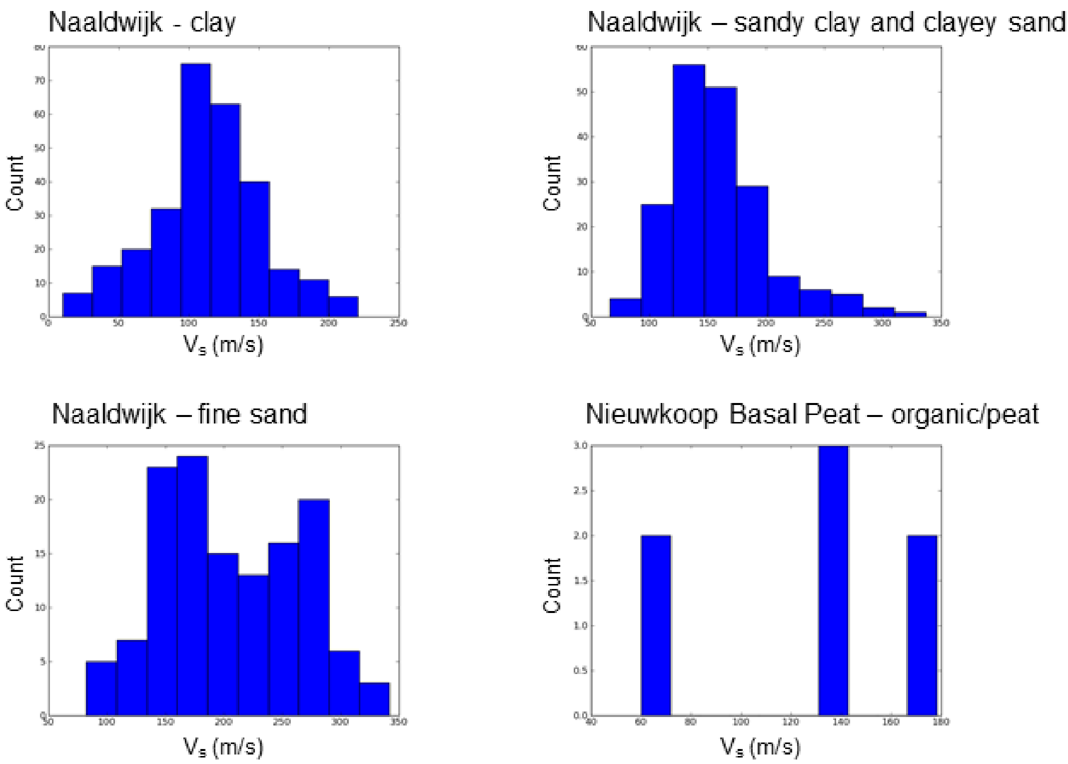

Figure 4.9 Distibutions of V_s derived from SCPTs for lithostratigraphical units distinguished in the Naaldwijk Formation. Top left: clay, top right: clayey sand and sandy clay, bottom left: fine sand. Bottom right: Distribution of V_s derived from SCPT for Nieuwkoop Formation, Basal Peat Bed (organic/peat).

Table 4.10 Statistics for V_s, based on the SCPTs measured in Groningen

Litho-stratigraphical unit in GeoTOP	**Lithological class in GeoTOP**	**Average V_s (m/s)**	**Standard deviation (m/s)**	**Total count**
BX	Clayey sand and sandy clay	226.2	37.6	44
BX	Fine sand	262.2	66.5	239
BX	Medium sand	289.9	31.1	43
BX	Coarse sand, gravel and shells	312.6	11.9	2
DR	Fine sand	286.1	26.5	9
DR	Medium sand	300.1	22.1	10
DRGI	Clayey sand and sandy clay	233.0	55.5	20
EE	Clay	224.5	28.4	5
EE	Clayey sand and sandy clay	251.7	26.3	21
EE	Fine sand	256.8	19.1	25
NA	Clay	113.7	38.6	283
NA	Clayey sand and sandy clay	157.8	42.9	188
NA	Fine sand	206.4	58.4	132
NIBA	Organic deposits (peat)	126.6	41.9	7
PE	Clay	224.8	44.6	338
PE	Clayey sand and sandy clay	234.0	43.7	23
PE	Fine sand	285.6	43.1	231
PE	Medium sand	330.4	38.0	41

Step 3 Groningen specific look up table for V_s

For the units represented in the SCPTs, the statistics from Table 4.10 were included in the look up table for V_s. In the case of Nieuwkoop Formation, Basal Peat Bed, these values were overruled by expert judgement. For the units that were not represented in the SCPTs, we chose either values from a corresponding unit from Table 4.10 , a value based on Wassing et al. (2003) or a value based on expert judgement. The standard deviation of V_s includes error sources such as possible differences in operation during SCPT measurement by different companies, smearing effects due to the sampling interval of 1 m in SCPT, variations in grain size distributions, compaction and cementation within a lithological class and possible depth dependency.

In summary, the following principles were used in assigning V_s values in the look up table:

- The lithostratigraphical unit and lithological class of anthropogenic deposits were treated as one unit with one V_s value.
- NA, NAWA and NAWO were assigned V_s values and standard deviations of NA.
- NIHO, NINB, NIGR and BXSI1 (peat) were assigned V_s values and standard deviations of NIHO.
- BX, BXKO, BXWI, BXSI2 were assigned V_s values and standard deviations of BX.
- One value for V_s is assigned for medium and coarser sand.
- When data were too few to provide representative distributions, a fixed coefficient of variation of 20% the estimated V_s value was used. This is based on the average coefficients of variation for the values in Table 4.10.
- A default value of V_s = 190 m/s ± 40 m/s was chosen for voxel stacks that have less than 60 voxels available. These voxel stacks occur in deep sand excavation pits with water depths reaching to levels greater than NAP-20 m.

The resulting V_s look-up table based on SCPTs, and therefore valid for the top 30 m, is included in Appendix J.

In the V_s assignment, there are several sources of error for $V_{s.}$

- Uncertainties in lithological composition. This is covered by aggregation to geological area level assuming that the variability in lithology is contained in all voxels within the geological area.
- Smoothing effect on V_s values in the SCPT records, due to the fact that V_s is measured in 1 m intervals whereas lithological boundaries in general cross these intervals.
- Possible depth dependency of V_s: for a “clean” lithological class, without varying admixtures, a depth dependence of V_s is theoretically expected because of increasing compaction, and hence density, with depth. In several individual SCPTs, the V_s values increase with depth. This is probably due varying amounts of admixtures and degrees of cementation, and therefore a lithological effect, rather than true depth dependence. A generic depth dependent relationship that is valid for a particular lithological class can only be derived for sufficient numbers of V_s values versus depth for each combination of lithostratigraphical and lithological class. A complicating factor in the analysis is the regular measurement intervals and incongruity with the lithological boundaries. The current SCPT dataset is regarded too small to be able to conclude whether V_s is depth dependent or not. Therefore, variations of V_s with depth within lithostratigraphical – lithoclass combinations are ignored in the current analysis and are part of the standard deviation of V_s.

- Uncertainty in the V_s for the combinations that were not represented by the available SCPT data. V_s values were assigned based on similar units in SCPT data, the look up table from Wassing et al. (2003) or expert judgement. A coefficient of variation of 20 % was adopted in these cases.

4.6.4 Construction of V_{s30} map for Groningen

The steps taken to construct a new V_{s30} map for the Groningen gas field (+5 km buffer) based on the GSG-model and the improved look up table for V_s are summarised below:

1. For each voxel of the GeoTOP model containing the lithostratigraphical unit and most likely lithological class, a V_s value is drawn from the distribution of V_s from the corresponding lithostratigraphical unit – lithological class combination in the look up table. The assumption is that the values of V_s are normally distributed and therefore the distribution can be characterised by the average V_s and its standard deviation. Additionally, no spatial correlation between V_s is assumed: a value for V_s for a lithostratigraphical unit – lithological class combination is drawn independently from a V_s value for the same lithostratigraphical unit – lithoclass combination in an adjacent voxel in the voxel stack.
2. A voxel stack of 30 m thickness contains 60 voxels of 0.5 m thickness each. Each of the 60 voxels receives a V_s by the process described in step 1.
3. The V_{s30} is calculated for the voxel stack, using the following harmonic mean equation:
$$V_{s30} = \frac{60}{\sum_{i=1}^{60}\left(\frac{1}{V_{s\,i}}\right)}$$
4. This procedure is repeated 100 times for each voxel stack, in order to capture the uncertainties in V_s. This results in 100 V_{s30} values for each voxel stack.
5. The aggregation to geological area level is needed to capture uncertainties in lithological infill within the geological area. The lithological class represented in each voxel is the most likely of a probability function determined in GeoTOP. However, with respect to the probability of lithological successions no realisations of voxel stacks have been calculated. Instead, the average V_{s30} and the standard deviation are calculated for all voxels stacks within one geological area. For example, for a geological area containing 400 grid cells of 100 m x 100 m, and thus 400 voxel stacks, there are 400*100 V_{s30} values. The average and standard deviation is calculated for these 40,000 observations in this geological area, assuming that the lithological variability is represented by a sufficiently large number of samples.

The resulting V_{s30} for each geological area is plotted on two maps (average and standard deviation). A side effect from the aggregation of the V_{s30} result to the level of geological areas is that sharp steps in V_{s30} occur at boundaries between the geological areas. The effect of sharp or more diffuse boundaries on the hazard and risk analysis is point of particular interest in the future.

4.7 Caveats and future work

Regarding the method of schematisation, we identified the following caveats:

- Version 1 of the GSG-model consists of separate results for two depth ranges. The combination of these two depth ranges needs to be performed by experts to ensure a geologically sound continuity.
- Dwelling mounds were not treated with special attention in version 1 of the GSG-model. They were included as in GeoTOP, where all man made soil bodies, such as dwelling mounds, embankments and landfills, are merged into one anthropogenic lithostratigraphic unit with uniform lithology (one lithological class). In general, modern man made bodies are sandier, while ancient ones are more organic. This distinction is not included in GeoTOP, and therefore not (yet) in the GSG-model.
- Since soil layers sensitive to amplification and soil layers sensitive to liquefaction consist of different lithological materials, the GSG-model constructed in this phase for site amplification cannot directly be translated to application for the liquefaction estimates. The geological areas for site amplification are based on extents of clay and peat layers, whereas specific types of sands are sensitive to liquefaction. Therefore, a geological model for liquefaction purposes needs to be constructed separately.
- For the look up table for V_s: not all V_s entries are based on SCPT data, since not all combinations of lithostratigraphy and lithological class were represented by the available SCPTs. Part of the V_s look up table is based on expert judgement.
- We assume that the V_s distributions are Gaussian.
- Depth dependency of V_s was not taken into account. This variation is currently included in the standard deviation of the V_s derived from the SCPTs.
- Aggregation of results (e.g. V_{s30}) to the level of geological areas leads to sharp steps at the boundaries of the geological areas. In reality, geological variations tend to be gradual.

For the next version of the GSG-model and derived products such as V_{s30} maps and site response calculations, we anticipate the following future developments for the method of schematisation:

- Assess the treatment of dwelling mounds in the GSG-model, since they have cultural heritage value. The assessment needs to be based on the characterisation of the composition of dwelling mounds, from geophysical fieldwork campaigns. If needed, a dwelling mound profile type can be added to the GSG-model.
- Construct a GSG-model dedicated for liquefaction purposes.
- Improvement of V_s relation (static look up table or including geographical relations) by including more SCPT data and generic relations between lithology, cone resistance q_c from CPT and V_s values. New Groningen-specific relations for V_s, based on CPT parameters, can be derived using neural networks. This approach will lead to a considerable improvement in the spatial coverage of V_s. In the coming months, Deltares plans to acquire 23 new SCPTs for NAM at the KNMI accelerograph stations. This is work in progress.
- With the planned increase in SCPT set, there will probably be more combinations of stratigraphical unit and lithology in the Groningen field represented in the SCPTs than in the current set. However, if there will still be combinations missing, we recommend measuring additional SCPTs and ensure to cover all combinations in the dataset.
- With the planned increase in SCPT set, depth dependency of V_s can be investigated and – when present – included in the next version of Groningen-specific V_s relations. For the new campaign of acquiring SCPTs we recommend to adjust the measurement

intervals for the subsequent SCPT according to the lithological boundaries. This can be done by first measuring and interpreting a CPT and then placing a CPT/SCPT next to it. Similarly, depth dependence of cone resistance q_c will be investigated when the complete Groningen CPT data set is included in the q_c-V_s analysis. Including depth dependency of V_s, when present, will probably lead to a decrease in standard deviation of V_s.

- Extend V_s relations to reference baserock horizon by combining information from:
  - CPT and SCPT (to a depth of 30 m).
  - Reprocessed surface wave data from 3D seismic surveys by Shell (to a depth of approx. 120 m)
  - V_p-V_s relations and deep sonic logs measured by NAM (depth range from 70 m to 3 km).
  - V_p-V_s relations and shallow sonic logs (to a depth of 200 m) at new vertical seismic array locations measured by Deltares.
- The effect of sharp or more diffuse boundaries on the hazard and risk analysis is point of particular interest.

5 Quality control

5.1 Introduction

The schematisation work for the surface to NAP-50 m depth range has been performed by different teams. The composition of the teams has been rotated frequently to ensure the fine-tuning of different approaches, insights and methods between the teams and to promote a consistent way of schematisation.

During and after finishing the schematisation work, the quality of the GSG-model for Groningen has been controlled and assessed in several ways:

- A quality check was performed for the Loppersum pilot, after completion of the schematisation for the surface to NAP-50 m depth range for that area (section 5.2). The check consists of a comparison between scenarios in the Loppersum geological areas and GeoTOP.
- A consistency check was performed for the entire area of interest (Groningen gas field +5km buffer) after completion of the schematisation for the surface to NAP-50 m depth range for the entire field (section 5.3). For consistency, the following checks were made:
    - Consistent labelling of areas with corresponding profile type in the shapefile and scenarios in the schematisation spreadsheets.
    - Minimum area per polygon.
    - Remarks in the schematisation spreadsheets.
- A quality check was performed for the entire area of interest after completion of the schematisation for the surface to NAP-50 m depth range for the entire field (section 5.3). For quality, the following checks were made:
    - Comparison of the version 1 GSG-model geological area boundaries with e.g. soil map, AHN, MIPWA glacial till extent and surface water distribution.
    - Recognition of general geology in geological area patterns.
    - Data density distributions for geological areas for borehole records and CPTs.
    - Assessment of impact of adding additional CPTs to the database.
    - Comparison between scenarios and GeoTOP voxel stack summaries for randomly selected geological areas (similar to quality check for Loppersum).

The connection between the two depth intervals has not yet been made. Therefore, no quality check was performed for the full depth range.

5.2 Quality check Loppersum: scenarios and GeoTOP

In the schematization, geological areas of the shallow subsurface (surface to NAP-50 m depth range) were defined and their geological build up in terms of lithofacies was described in one or more scenarios. These geological areas are based on the available information (chapter 3).

In this method, it is assumed that the identified geological areas from the schematization are uniform areas in GeoTOP as well. To check this assumption, several figures were made to compare the results from GeoTOP and from the scenarios. Examples of figures used for this are figures that summarize the lithological composition of all voxel stacks within one geological area and scenarios (e.g.Figure 5.2) and profiles drawn in iMOD (e.g. Figure K.1 to Figure K.3 in Appendix K).

In general and based on a qualitative comparison, the voxel stack summaries of Loppersum correspond well with the constructed scenarios. Geological area 2010 is used as an example in this section to illustrate the comparison. The location of geological area 2010 is shown in Figure 5.1. General observations of other geological areas are included in Appendix K.

Part of the differences between the voxel stack summaries and scenarios from the schematization is caused by model issues. Both GeoTOP and DGM v2.2 are regional models, whereas the scenarios often include local heterogeneities. Besides, both models have their technical limitations.

Several observations are valid for specific geological units, e.g. concerning the representation of peat in GeoTOP. Only a limited number of geological sequences are present in the municipality of Loppersum. The check has been performed for several geological areas adjacent to the municipality of Loppersum as well. The check will be repeated in a reduced fashion (compare scenario and summary of voxel stack for one geological area for each profile type) for the rest of the Groningen field (+5 km buffer) in a later stage.

Example: geological area 2010

For geological area 2010, the location is shown in Figure 5.1. The comparison between scenarios and voxel stack summary of lithologies in shown in Figure 5.2.

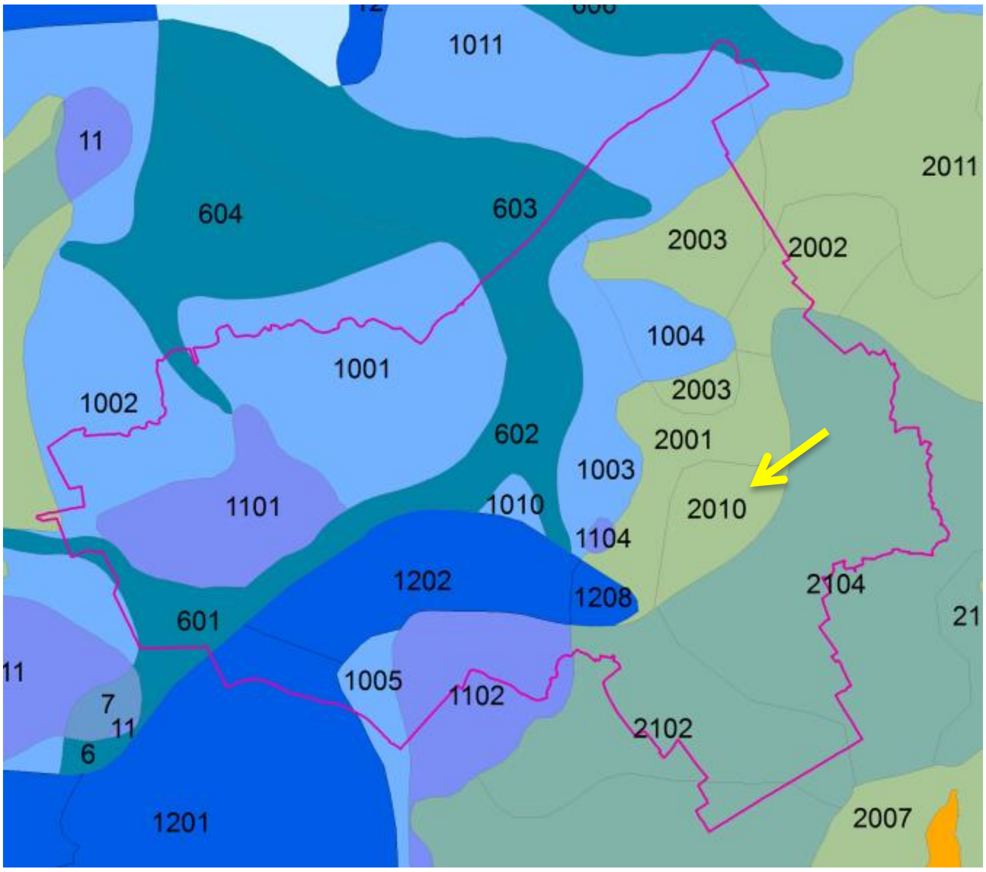

Figure 5.1 Location of geological areas in municipality of Loppersum. Geological area 2010 is indicated by the yellow arrow. The boundary of the municipality is represented by the pink line. The Loppersum check was performed prior to completion of constructing the GSG-model for the entire area of interest. Slight adjustments of boundaries of geological areas are therefore possible and the colour scale has been adjusted as well. The location of the Loppersum pilot within the area of interest is shown in Figure 1.1.

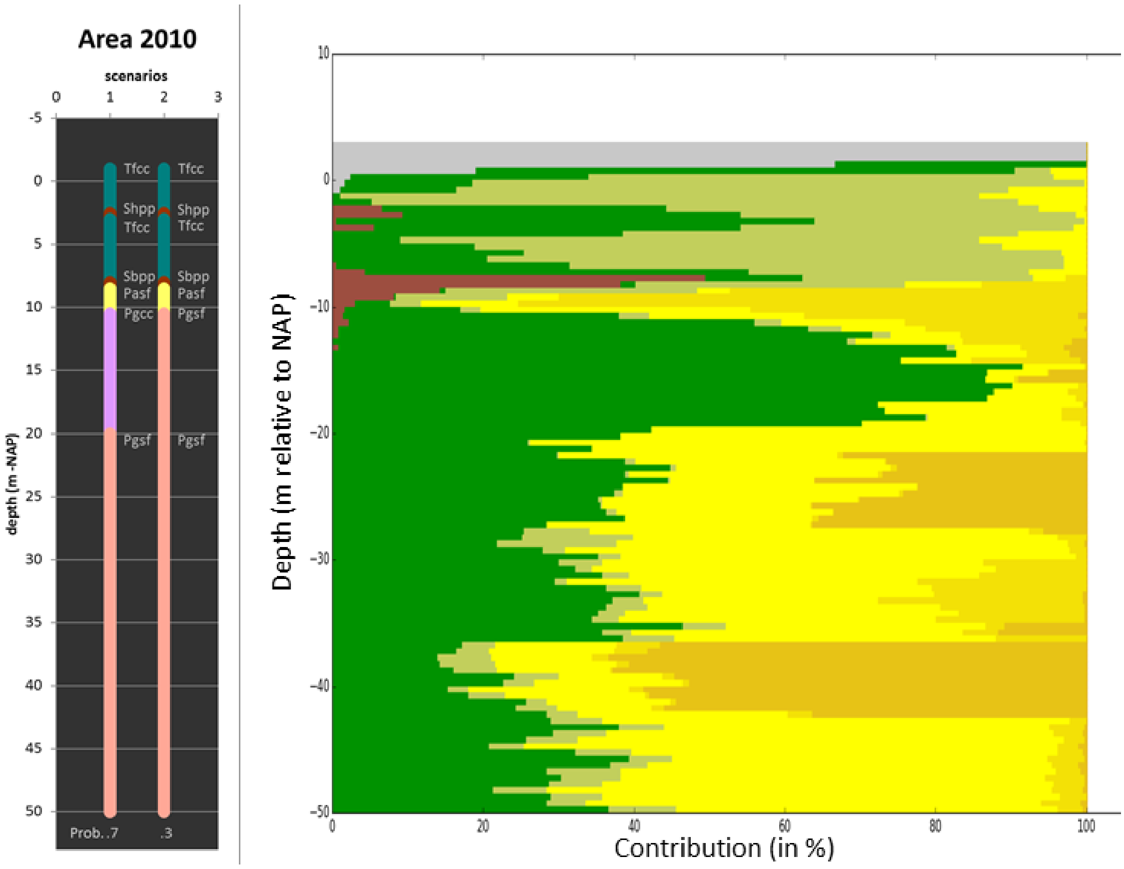

Figure 5.2 Comparison for geological area 2010. Left panel: visual representation of scenarios for the geological area, showing the two scenarios that were recognised during schematization. Key to the abbreviations: Tfcc (tidal clays), Shpp (Holland Peat), Sbpp (Basal Peat), Pasf (Cover sand), Pgcc (Potclay) and Pgsf (fine glacial outbreak sand). Right panel: GeoTOP voxel stack summary showing different lithological classes of the voxel stacks in percentages (green = clay, light green = sandy clay and clayey sand, brown = peat, light, medium and dark yellow = fine, medium and coarse sand, grey = man-made deposits).

The voxel stack summary shows the percentage of different lithologies per 0.5 m depth interval, averaged for all voxel stacks within the geological area. The voxel stack summary of geological area 2010 (Figure 5.2, right) shows from top to bottom: the anthropogenic layer, clay layer (NAP to NAP-3 m), layer with peat and clay NAP-3 to -5 m), mainly clay (NAP-5 to -7 m), peat (NAP-7 to -8 m), mainly sand with some peat (NAP-8 to -11 m), mainly clay with some sand (NAP-11 to -20 m), and belowNAP-20 m mainly sand with varying amounts of clay. The two scenarios (Figure 5.2, left) show from top to bottom: tidal clays, Holland Peat, tidal clays, Basal Peat, cover sand and either potclay or fine glacial outbreak sands.

In general, the scenarios (Figure 5.2, left) and the lithology summary (Figure 5.2, right) correspond quite well. The comparison is described from top to bottom:

- In the scenarios we observe tidal marine mudflat clay down to NAP-8 m. In GeoTOP this clay is clearly present, only partly sandier (and therefore assigned a different lithological class). This can be a generalization in the schematization of small sandy clay layers.
- In the top 10 m, two peat intervals are identified in the scenarios, both present for 100% of the geological area. Both are well represented in GeoTOP, but the given probabilities differ. In GeoTOP, the Holland peat (Shpp) layer is present in only 10%

of the voxel stacks and the basal peat (Sbpp) in 50%. For the Holland peat, this seems to be a slight underestimation. In general, the schematization overestimates the presence of peat layers.
- Around NAP-10 m the unit fine cover sands (Pasf) is schematized. This can be clearly recognized in the GeoTOP stacks; the occurrence of sand suddenly increases to almost 90% at this depth. Between NAP-10 and -20 m there is 70% probability of Potclay in the scenarios. This clay peak corresponds very well with the GeoTOP voxel stacks: the occurrence of clay here is on average 75-80%.
- The most problematic part of this profile is below NAP-20 m (Pleistocene). In GeoTOP, there is a probability of 30% clay on average, while the scenarios indicate fine glacial outbreak sands (Pgsf). In GeoTOP, more coarse sand intervals are observed. This difference can have several causes and is further elaborated upon in the general and unit-specific remarks in Appendix K. One possible cause is that there are almost no deep drillings in this region available to schematize, while GeoTOP uses information from wells further away or a random stochastic infill.

The Loppersum pilot check shows that there are several differences between the GeoTOP infill and the scenarios defined in the schematisation. Since the following steps in the analysis will be based on the GeoTOP voxel stacks, rather than on the scenarios, the peculiarities of GeoTOP need to be taken into account. This means, for example, that for areas with overrepresentations of peat in the shallow subsurface, the site response might be overestimated. The impact of the issues described in this section for geological area 2010 and the general remarks in Appendix K need to be assessed during the coming sensitivity study. We recommend performing a check of the Loppersum site response result against the observations made in the Loppersum quality check.

5.3 Consistency check of surface to NAP-50 m

The variation in site response in the province of Groningen is related to the heterogeneity of its subsurface. The lithological configuration is represented in the geological area map, which is based on schematisation of all different profile types in the area of the Groningen gas field (+5 km buffer). This chapter describes the checks and resulting findings of the NAM-schematisation Quality Control (QC) assessment. The Quality Control was performed for the shallow (surface to NAP-50 m) subsurface schematisation, since this part of the work was carried out by a team of 15 geologists.

5.3.1 Consistency and quality checks

During schematisation, two or three teams of two persons each worked jointly in a project room simultaneously. During the work, there was frequent interaction between the teams. To ensure a similar routine, the team composition rotated frequently. In this way, experiences were shared among the total group.

Although the workflow described in section 4.3 was followed by every team member, there are personal differences. For example, there were differences in the degree of use of e.g. AHN. To eliminate the personal preferences in the resulting GSG-model, a geologist performed a consistency check after completion of the GSG-model for the entire area of interest. Changes were made to the model to be able to deliver a consistent GSG-model to NAM.

The consistency checks and subsequent actions to improve the subsurface model are summarised in Table 5.1. Several actions are illustrated by figures and an additional description in section 5.3.2.

Table 5.1 QC checks, with actions and results

Number	Check	Action	Result
1	Check shapefile attribute table labelling.	Labels should match the profile-type class. If not, adjust the labels in the attribute table.	Adjustment of the attribute table of the geological area shapefile.
2	Check the (minimum) area per polygon. A minimum value of 25 voxels (equivalent of 500 x 500 m) is required.	If this minimum value is not met: check on the contents of the polygon, not on solely the minimum area. Merge when possible.	15 polygons did not match the criteria and were re-examined. 11 polygons were retained as small, because of their distinct geological build up relative to the neighbouring polygons. Four polygons were merged with neighbouring polygons.
3	Check the 'remarks' in the schematization spread sheets.	Depending on the comments	For 52 polygons schematization was adjusted, remarks were corrected or removed. See also section 5.3.2.
4	Check consistency between scenarios in the spreadsheets and the profile types in the shapefile for each geological area.	If not consistent, the described profile-type should be transferred to the correct profile-type. This means renumbering the scenario in the spreadsheet and the polygon in the shapefile.	55 polygons/schematizations were reassigned to other profile types, or adjustments to the schematizations were made in order to fit its profile-type class. See also section 5.3.2.
5	Check the mapped profile-type polygon-extents with the digitally available soil map.	If large differences exist, investigate the origin of it and adjust when necessary.	No differences exist. The digitally available soil map and the recent 'Veen actualisatie kaart' of Alterra were used as input for the GeoTOP shapefiles. Therefore, the outlines were included in the first draft of geological areas.
6	Check the mapped polygon-extents with the AHN.	If large differences exist, investigate the origin of it and adjust when necessary.	Some inconsistencies noted (Figure 5.3, section 5.3.2). Adjustments were not made based on AHN (see recommendations, section 5.4).

Table 5.1, continued. QC checks, with actions and results

Number	Check	Action	Result
7	Check the mapped polygon-extents with surface water distributions.	If large differences exist, investigate the origin of it and adjust when necessary.	There are several inconsistencies in the treatment of surface water in the geological areas (Figure 5.4). Adjustment of geological areas for Wadden Sea region (section 5.3.2).
8	Check the mapped polygon-extents with the MIPWA glacial till extent.	If large differences exist, investigate the origin of it and adjust when necessary.	The MIPWA glacial till extent (including the newest insights) was used as input for the GeoTOP shape files. Therefore, MIPWA information is automatically incorporated.
9	Check whether geology can still be recognised in the resulting geological areas	Maps containing overlays between version 1 geological areas (Figure 6.1) and the maps showing the extent of several geological formations (Figure 2.6).	The extents are recognisable in various boundaries of geological areas (section 6.1).
10	Check the density of available digital borehole descriptions and CPTs per polygon.	Maps of borehole data density and combined borehole+CPT density are included in section 6.3. No immediate action taken.	During interpretation of site response results take into account the data density. Possibly improve subsurface model in later stage of the project when new CPTS become available in data sparse regions.
11	Check the use of the latest insights for the occurrence of peat in the northern part of the Netherlands.	If large differences exist, investigate the origin of it and adjust when necessary.	The newest insights of the extent of niho and niba that were used in the GeoTOP shapefiles are considered “good” according to experts.
12	Evaluation of the internal consistency of the polygons, similar as done for the Loppersum pilot (section 5.2 and Appendix K).	Comparison of the spreadsheet scenarios and the voxel stack summaries of GeoTOP for 10% of the geological areas (random selection).	75% of the checked scenario plots of schematisation correspond well with the GeoTOP voxel stacks summaries. Special attention is needed for the Wadden Sea polygons. See also Appendix L.

Table 5.1, continued. QC checks, with actions and results

Number	Check	Action	Result
13	Assessment of the impact of addition of extra data to the robustness of the geological areas. For several areas for which additional CPTs (e.g. from Fugro) that were made available but were not used in the schematisation so far.	If needed, adjust boundaries of geological areas.	Confirmation of boundaries of geological areas, no adjustments needed. Possible use for additional CPTs for better constraints on GeoTOP voxel content. See also Appendix M.

5.3.2 Descriptions of selected checks

In this section, several selected checks are described.

Inconsistent use of Aaop (check 3)
The Aaop facies (anthropogenic layer) was not used in a consistent way by the teams. In some cases, Aaop is included in the scenarios; in others the layer is not included while GeoTOP indicates the presence of an anthropogenic layer. Additionally, in some cases the presence or absence of Aaop is used as a reason to split a polygon. As a consequence, the top 1 m of the model is not schematised consistently throughout the model.

Inconsistent use of lithofacies codes (check 3 and 4)
A few lithofacies codes were not used consistently by the different teams in the spreadsheet schematisations. These are:

- Both Pgsc (fluvioglacial, coarse gravelly sand, gravel beds, boulders) and Pfsc (fluvial channel belt, coarse to very coarse sand) were used to describe coarse to very coarse (glacio)fluvial sands.
- Both Pxlp (various, low permeability clay/loam) and Ptcc (mudflat, clay with some sand/silt beds) were used to describe clay/silt occurrences at larger depths.
- Both Pfsc (fluvial channel belt, coarse to very coarse sand) and Pgsf (glacial outbreak, fine sand) were used to describe 'glacial outbreak' deposits (coarse and fine).

AHN (check 6)
From a quick first check with AHN it appeared that there are inconsistencies in the application of AHN data during schematization. Traceable and mappable entities on the AHN are not always identified and incorporated in the geological areas (Figure 5.3). Adjustments were not made based on AHN (see recommendations, section 5.4).

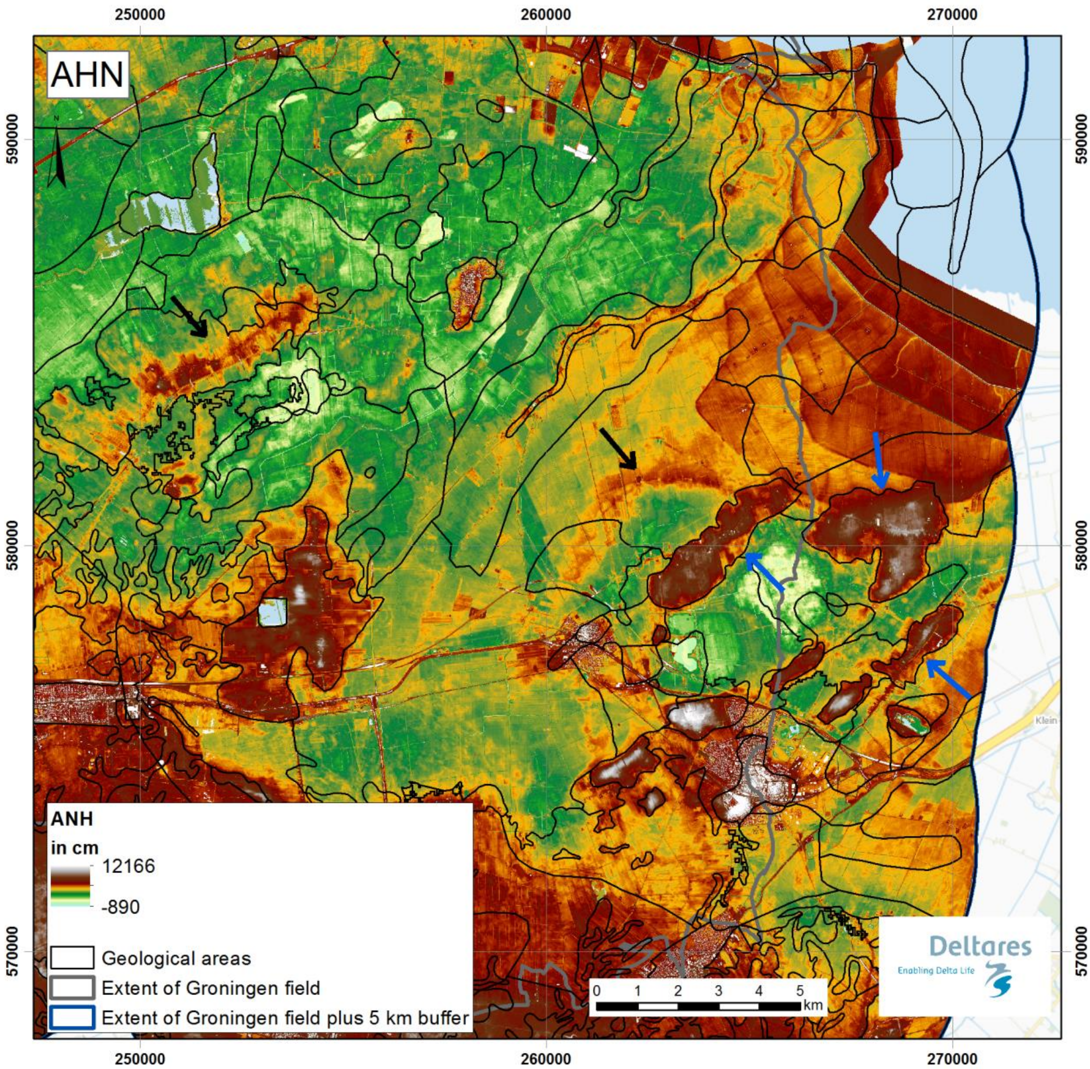

Figure 5.3 Detail of area of interest, showing the AHN in colour-coded grid and the outline of geological areas. In some case, AHN clearly coincides with geological area boundaries (e.g. blue arrow), while in other cases variations in topography suggesting cover sands (and thus expected differences in subsurface composition) are ignored (black arrows).

Onshore and offshore (check 7)

During schematisation, no special attention was paid to polygons containing both offshore and onshore parts (i.e. land and Waddenzee). In some cases, large surface waters were defined as separate geological areas (for example, blue arrows in Figure 5.4), whereas in other regions, surface waters were included as part of a geological area (for example, black arrows in Figure 5.4). This resulted in polygons with strong heterogeneous lithological content and generalised and averaged scenarios. This is specifically the case for the Wadden Sea region (upper right corner in Figure 5.4). During QC, we decided to split polygons containing Wadden Sea into two parts: one for the land and one for the sea part. The Rijkswaterstaat shapefile containing the sea defence dyke (Nationaal Basisbestand 2012 Dijkringgebieden, version 4.0) was used as separator. For the harbour of Delfzijl and the Eemshaven, we manually adjusted the separation line in order to include the harbour areas to the land parts.
Because of the separation, the scenarios in the spreadsheets for polygons of both land and sea neither represent the onshore nor the offshore part correctly.

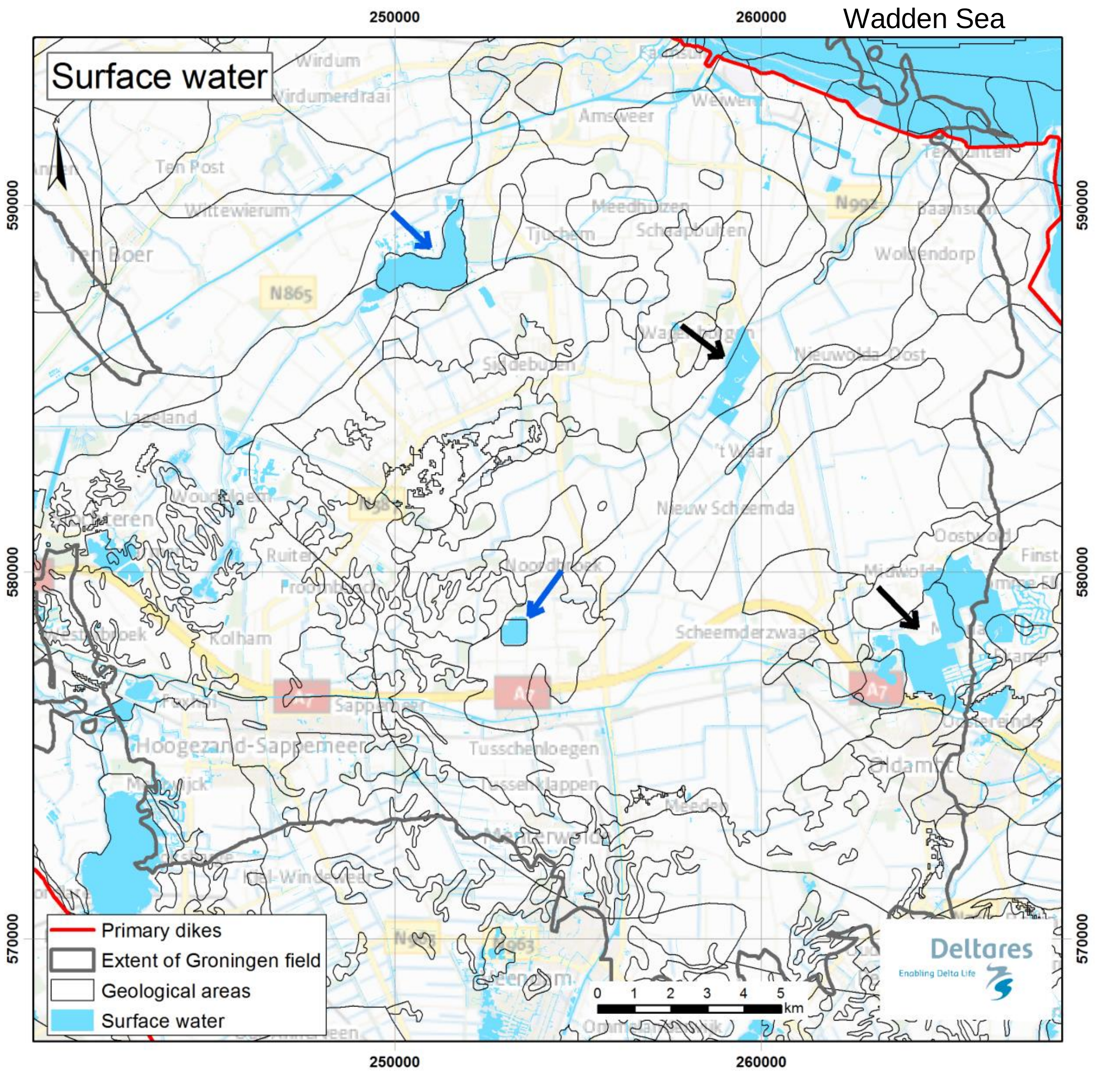

Figure 5.4 Detail of area of interest, showing the outlines of the geological areas (black lines) and surface waters (blue areas). In some case, surface water extent coincides with geological area boundaries (blue arrows), while in other cases surface water extent was not considered critical for geological area definition (black arrows).

Other surface waters (check 7)

No consequent attention was paid to polygons containing inland lakes (e.g. Blauwe stad). The presence of inland lakes can cause strong lithological heterogeneity within a polygon, resulting in an incorrectly representation of the lithology by the polygon. In version 1 of the GSG-model, no adjustments were made for the bodies of surface water. In the next version, surface waters could be marked as “inactive” to exclude them from further analysis of site response analysis.

5.4 Caveats and future work

During quality control, we identified the following caveats:

- GeoTOP issues with respect to the application of site response, such as the representation of peat and Peelo Formation in GeoTOP voxels, were identified as points of attention in the quality control.
- There are inconsistencies in schematisation of the anthropogenic deposits including dwelling mounds and filled up canals. In general, they are schematised as one profile type unit or scenario (schematisation) and as one stratigraphic unit (GeoTOP). These anthropogenic deposits, however, differ in composition depending on origin and age. As a consequence, they might respond differently to earthquake shaking and show a range of site responses.
- The difference in subsurface composition between onshore and offshore (including inland lakes) regions is not (systematically) taken into account during schematisation of the shallow subsurface. At the final stage of version 1 GSG-model, the polygons containing both land and sea were split into land and sea parts. The scenarios were constructed before this split and are therefore not representative of either land part or the sea part. Since the scenarios will not be used in the following analysis of site response calculations, the impact is not large. However, attention needs to be paid to the extent of the split polygons. In the next version of the GSG-model, these polygons need to be reassessed.
- There are inconsistencies in schematisation for AHN and inland surface water distributions. In some cases, elevations (AHN) or water bodies can be clearly recognised in the boundaries of geological areas, whereas in other cases the boundaries are not related to changes in elevation or presence of surface water. We recommend performing site response calculations first and later assess whether adjustments in geological area boundaries are required.
- Recently reclaimed areas such as Eemshaven and in Delfzijl are sensitive to compaction. These areas were not designed accounting for earthquakes, since the guidelines (NEN-NPR) were not effective when these areas were designed and built. They might show site response that differs from areas with similar subsurface composition below the landfill material.

For the next version of the GSG-model, we recommend to include the following items derived from the quality control:

- Include information on dwelling mounds from future fieldwork campaigns to improve the characterisation of the anthropogenic lithoclass.
- We propose to exclude the Wadden Sea part from the area of interest, since no houses or other buildings are present in this region. However, the schematisation was performed based on information from both sides of the Wadden Sea dike. When we pursue to exclude the Wadden Sea, the polygon containing both land and sea need to be checked for their appointed scenarios and the location of the boundaries between the geological areas.
- We propose to deactivate the voxel stacks containing inland surface water (possibly with a minimum area) during site response calculations, because the voxel stack is not representative for the remainder of the geological area. We can either define a masking “surface water shapefile” or preserve the surface water in the geological areas but make individual voxels inactive. Regions with spatially close alternations between land and surface water (e.g. Blauwe Stad) will need special treatment.
- Evaluation of the results of the site response calculations before determining the need for adjustments e.g. due to data density issues or inconsistent use of AHN and inland

surface waters during schematisation performed so far. Pay special attention to site response at reclaimed land areas.