



Assembling the ground model and the derived values

*Guidelines for the application of the 2nd generation of Eurocode 7:
Geotechnical design*

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Abstract

The Ground Model is defined in the second generation of Eurocode as a 'site-specific outline of the disposition and character of the ground and groundwater based on results from ground investigations and other available data'.

The Ground Model is a compilation of data including maps, plans, sections, and reports that capture objective information regarding the soil and rock types as well as groundwater conditions across the zone of influence. The Ground Model should cover the site and the surrounding area to provide the geotechnical and geological context, potential sources of materials for construction, and the surrounding conditions that may influence the groundworks. The Ground Investigation Report referred to in the Ground Model should be treated as one factual data source for the site's ground and groundwater information.

As the Ground Model is an illustration based on derived values and interpolation between factual data, including the distribution of the geotechnical units within the zone of influence, the model itself is the most likely illustration based on the available data during that phase of a project. Inherent uncertainties to such Ground Models may be quantified and reduced during subsequent project phases when more data becomes available.

The Ground Model includes, but is not limited to, the following components within the zone of influence:

- rockhead & structural geology
- superficial geology and geomorphology
- seismicity
- hydrogeological conditions and
- geotechnical and geochemical conditions

The derived value of a ground property is a value of a ground property obtained by theory, correlation, or empiricism from test results or field measurements. Derived values presented in the ground investigation report (GIR) are the source for representative values of ground properties to be used in ultimate and serviceability limit state verifications.

Data gathered during desk study, site inspection, preliminary and design investigations, and ground and structure monitoring are to establish derived values of ground properties.

Foreword

JRC Foreword

The construction ecosystem is of strategic importance to the European Union (EU), as it delivers the buildings and infrastructures needed by the rest of the economy and society, having a direct impact on the safety of persons and the quality of citizens' life. The construction ecosystem includes activities carried out during the whole lifecycle of buildings and infrastructures, namely design, construction, maintenance, refurbishment and demolition. The industrial construction ecosystem employs around 25 million people in the EU and provides an added value of EUR 1 158 billion (9.6% of the EU total)^{1,2,3}.

The construction ecosystem is a key element for the implementation of the European Single Market and many other important EU strategies and initiatives. The European Green Deal ([COM\(2019\) 640 final](#)) aims to achieve climate neutrality for Europe by 2050, and relies on numerous initiatives, noteworthy:

- the New Circular Economy Action Plan ([COM\(2020\) 98 final](#)) and the New Industrial Strategy for Europe ([COM\(2020\) 102 final](#)) intending to accelerate the transition of the EU industry to a sustainable model based on the principles of circular economy;
- the revision ([COM\(2022\) 144 final](#)) of the Construction Products Regulation ([Regulation \(EU\) No 305/2011](#)) aiming to enable the construction ecosystem's contribution to meeting climate and sustainability goals and embrace the digital transformation of the built environment;
- the New EU Strategy on Adaptation to Climate Change ([COM \(2021\) 82 final](#)) supported by the recent Commission Communication on managing climate risks ([COM\(2024\) 91 final](#)) that reinforces the need to address climate change concerns to guarantee resilience and sustainability of built structures and infrastructures and to ensure regular science-based risk assessments;
- the first European Climate Risk Assessment ([EUCRA](#)) report which highlights the importance of EU policies for the built environment, including updating construction standards and related European datasets.

Furthermore and recognizing that the EU's ambitions towards a climate neutral, resilient and circular economy cannot be delivered without leveraging the European standardization system, the European Commission presented a new Standardization Strategy ([COM\(2022\) 31 final](#)). The strategy spots standards as *“the silent foundation of the EU Single Market and global competitiveness”*.

The EU has put in place a comprehensive legislative and regulatory framework for the construction sector, including European standards (EN). Within this framework, the [Eurocodes](#) are a series of 10 European standards, EN 1990 to EN 1999, providing common technical rules for the design of buildings and other civil engineering works. In fact, the Commission Communication on managing

¹ Commission staff working document: Scenarios for a transition pathway for a resilient, greener and more digital construction ecosystem (<https://ec.europa.eu/docsroom/documents/47996>)

² Council of the EU, Press release 30 June 2023, <https://www.consilium.europa.eu/en/press/press-releases/2023/06/30/council-adopts-position-on-the-construction-products-regulation/>

³ Transition Pathway For Construction, European Commission, DG GROW, <https://ec.europa.eu/docsroom/documents/53854>

climate risks directly mentions the Eurocodes, highlighting the role of building and infrastructure standards in integrating climate adaptation and resilience.

The [Commission Recommendation 2003/887/EC](#) on the implementation and use of the Eurocodes for construction works and structural construction products recommends undertaking research to facilitate the integration into the Eurocodes of the latest developments in scientific and technological knowledge. In this context, the so-called second generation of the Eurocodes is under development under Mandate M/515 and expected to be available by 2026. The second generation Eurocodes incorporates improvements to the existing standards and extends their scope by embracing new methods, new materials, and new regulatory and market requirements, including considerations for climate change impact on structural design.

In order to support the implementation of the second generation EN 1997 “Geotechnical Design”, CEN Technical Committee 250/Sub-Committee 7 (TC250/SC7) produced a series of guidelines addressing the most important new aspects in the standard. The series of guidelines contains the following documents:

- Guideline C1 – “Determination of representative values from derived values for verification of limit states with EN 1997”
- Guideline C2 – “Assembling the Ground model and the derived values”
- Guideline C3 – “Reliability-based verification of limit states for geotechnical structures”
- Guideline C4 – “Implementation of design in execution and service life”

Within the framework of Administrative Arrangements between the European Commission’s Joint Research Centre (JRC) and DG GROW on support to policies and standards for the construction ecosystem, JRC is engaged in activities facilitating the implementation and practical use of the second generation Eurocodes. In this context, the guidelines by TC250/SC7 are published as JRC technical reports, part of the series “*Support to the implementation, harmonization and further development of the Eurocodes*”.

We hope that this report will provide a sound and helpful basis for the implementation and use of the second generation EN 1997 “Geotechnical Design” and contribute to training and education of the professionals engaged in geotechnical design, supporting further skills development for individuals' careers and also EU's competitiveness. The report is available to download from the “Eurocodes: Building the future” website (<http://eurocodes.jrc.ec.europa.eu>).

The authors have sought to present useful and consistent information in this report. However, users of the information contained in this report must assess if such information is suitable for their purposes.

Ispra, September 2024

François Augendre, Head of Unit
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European Commission

CENT/TC 250/SC 7 Foreword

With the adoption of the 2nd Generation of Eurocode 7 – Geotechnical design – Member States will need to implement new procedures in many different topics, not considered in the first generation of the Code, such as the assessment of Representative values, the Ground Model, the use of Reliability methods and the implementation of design in the execution phase. To facilitate the implementation of Eurocode 7, CEN Technical Committee 250/Sub-Committee 7 (TC250/SC7) therefore decided to produce a suite of Guidelines, one for each of the most relevant new aspects, to help ensure that the objectives of the code writers are reached in practice.

According to Clause 4 of Eurocode 7, Basis of design, the fundamental step to ensure that the prescribed reliability in geotechnical design is reached, is the development of a representative geotechnical design model being the combination of the Ground Model and the set of design values of relevant geotechnical properties needed for verifications.

The first Guideline of the suite addresses the fundamental process of determining design values of geotechnical properties from derived values obtained from various ground investigation activities. Once the representative values of properties, either characteristic (through statistical evaluation) or nominal (cautious estimate), are determined, design values are obtained by applying the partial factors for a design situation.

The second guideline addresses the process of assembling the Ground Model, highlighting the importance of progressive upgrading the Model with an increase in knowledge of the ground within the zone of influence of the specific structure. Note that the concept of the zone of influence in the second generation of Eurocode 7 is sensibly widened after environmental and seismic aspects have become central in planning the Ground Investigation and processing the results.

A significant novel aspect is the use of Eurocode 7 in combination with reliability-based methods. This is likely to lead to a very important evolution of safety assessments in geotechnical design in the coming years. Eurocode 7 like other Eurocodes is fundamentally reliability-based although safety verifications are tied to the application of partial factors. However, in the second generation of Eurocode 7, Clause 4 explicitly states that reliability-based design is only one of the options to verify limit states in geotechnical design. As these methods are not usually addressed in most of the teaching programs, it has been decided to dedicate a specific guideline to reliability-based verification of limit states coherently with the safety concepts of the Eurocodes. Moreover, the objective of this third Guideline is to provide information for code developers to perform reliability calibration of partial factors given the preparation of National Annexes.

It is well known by geotechnical designers that a great contribution to the reliability of a geotechnical construction relies upon its execution and its real performance. This is why Eurocode 7 now specifically dedicates a full clause in EN 1997-1:2024 to the implementation of design during execution and service life. The fourth Guideline presents measures to ensure that the design is correctly implemented in the different construction phases and how to document the activities carried out to this scope on the construction site. After a general description of the suggested rules and methods, the guideline describes good practice for establishing a Supervision Plan, Inspection Plan, Monitoring Plan and Maintenance Plan, how to establish acceptance criteria and limit values and gives contingency measures that might be utilized when an acceptance criterion/limit value is reached. This is implemented for typical geotechnical constructions such as embankments, bored piles, rigid inclusions, and groundwater control.

The upgrading of Eurocode 7 to the methods of modern Geotechnics was a very difficult task that has been achieved thanks to the strong involvement of many dedicated people from all European

countries. However, this process cannot be considered concluded with the publication of the new Eurocode documents alone and there will be a long route to implementing Eurocode 7 into the engineering practices of the many countries involved.

The involvement of the many members of the Task Group C1 to C4 of SC7, who prepared these Guidelines is very gratefully acknowledged. These Task Groups have performed tremendous work over almost 4 years to compile knowledge and experience in European geotechnical engineering to draft these Guidelines.

It is therefore strongly believed that for the transition from the 1st to the 2nd Generation of Eurocode 7, these Guidelines will be very helpful in clarifying the new concepts and methods. The Guidelines will also provide didactic background material that could not be presented in the Code.

Giuseppe Scarpelli, Coordinator Task Groups C1 to C4

Adriaan van Seters, Chairman

CEN/TC250/SC7 'Geotechnical Design'

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Belgium, Estonia, Finland, France, Germany, Italy, Latvia, Luxembourg, Netherlands, Norway, Poland, Portugal, Romania, Slovakia, Spain, Sweden, Switzerland, and the United Kingdom.

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1 Introduction

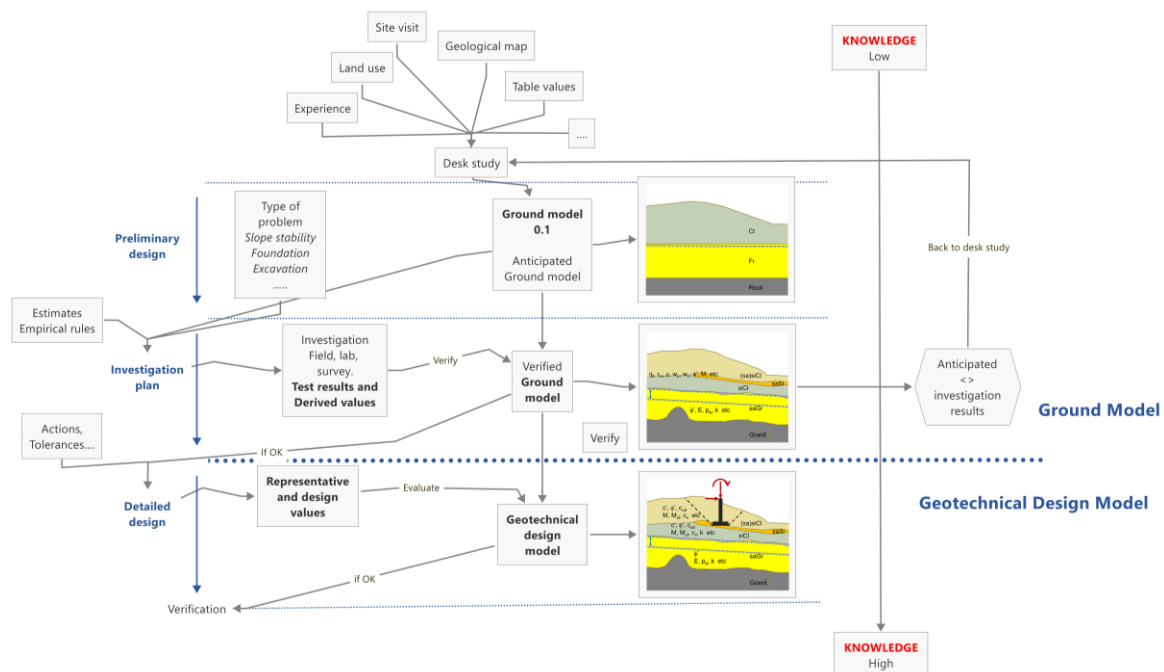
The Ground Model of the zone of influence (ZOI), for a project is defined in the Eurocode as a 'site-specific outline of the disposition and character of the ground and groundwater based on results from ground investigations and other available data'.

There are two distinct models in the 2nd generation Eurocode 7: the Ground Model (in EN 1997-2:2024), which includes geology and presentation and evaluation of test results, and the geotechnical design model (in EN 1997-1:2024), which covers the design of the structure, and so includes the selection of the geotechnical design parameters.

During the revision of the Eurocodes to arrive at these two models, there were different views across Europe as to what a Ground Model contains, hence the boundary between the 'Ground Model' and the 'geotechnical design model'. This guideline describes the Ground Model as a representation of the 'geological conditions', for which we can sensibly read the 'engineering geological conditions', including the presentation and evaluation of the test results into derived values. However, the inclusion and selection of design parameters develop this into the next step, which is a 'geotechnical design model'.

Figure 1 illustrates how the geotechnical design model (GDM) is an extension or development of the Ground Model but is a separate model in its own right. The GDM includes representative and design values of the relevant geotechnical properties for the structures under consideration for any specific design situation. This distinction between the Ground Model and GDM is important because both models are subject to ongoing review and update as additional information becomes available.

Figure 1. Relationship of Ground Model to Geotechnical Design Model.



Source: Garin et al. (2024)

The Ground Model is a compilation of data derived from several sources, including but not limited to maps, plans, sections, and reports that capture objective information regarding the soil and rock types as well as groundwater conditions across the zone of influence. The Ground Model should

cover the site and the surrounding area to provide the geotechnical and geological context, and information on the surrounding conditions that may influence the groundworks. The Ground Investigation Report, referred to in the Ground Model, should be treated as the factual data source for the site's ground information.

The ground Model is intended to use the distribution of the geotechnical units within the ZOI, together with an interpolation of factual data and, where appropriate, derived values, to produce the most likely indication of ground and groundwater conditions for this phase of a project.

Uncertainties inherent in the compilation of Ground Models must be quantified and described. A review of results, limitations, uncertainties, discrepancies and gaps in data should be recorded as part of the Ground Model development process. It is intended that uncertainties will be reduced during subsequent phases of a project when more data becomes available.

The Ground Model includes, but is not limited to, the following components within the zone of influence:

- rockhead & structural geology
- geometry of the layers
- superficial geology and geomorphology
- seismicity
- hydrogeological conditions
- geotechnical and geochemical conditions

Within the above list of components, seismicity brings unique and complex issues to the design of structures. With regard to the Ground Model and ground investigation activities, a greater depth of ground influence needs to be considered. Typically, in countries where seismic design is required, ground investigations extend down to 'seismic bedrock' ($V_s > 800$ m/s) or down to 30 m, whichever is the less deep. The guidance given in EC8 regarding seismicity should be followed where design is taking place in areas of known or suspected seismicity.

Development of the Ground Model should be commenced as early as possible, but in any case, as part of the desk study, using existing geological maps, previous investigations, reports, satellite imagery, photogrammetric and/or LiDAR (light imaging detection and ranging) data, site reconnaissance, and consideration of the site's geological history and geomorphology. The Ground Model should aim to capture the general composition and assembly of the soil and rock types and forms the basis of the field and laboratory investigation planning. The Ground Model must be verified with additional geotechnical, geological and hydrogeological data during the life of the project.

As the purpose of the ground investigation program is to reduce project-specific critical ground risks related to uncertainties in the Ground Model, investigations should not start before the development of the Ground Model has commenced.

The Ground Model should be developed alongside the compilation of the Ground Investigation Report (GIR). The horizontal blue dotted line in Figure 1 shows the delineation between the Ground Model and the GDM. All of the data and information relating to the ground and groundwater conditions for the Ground Model area should be captured and presented within the GIR.

As part of its development, the Ground Model will necessarily contain some interpretations of the geometry of geotechnical units (ground conditions) and groundwater conditions. However, the transition from the Ground Model, which essentially comprises a representation of factual data and is presented alongside the GIR, to the GDM, which is linked to the Geotechnical Design Report (GDR), needs to be understood and recognised. The GDM and GDR both comprise interpretative design information that makes use of and builds on the data contained in the Ground Model and GIR.

2 The purpose and process of the Ground Model

2.1 General

The Ground Model is a verbal/graphical/schematic tool and process that is used to advance knowledge of the ground and groundwater characteristics within the zone of influence of the structure (or structures) and to help identify the corresponding risks.

The assembling and use of the Ground Model should be a fundamental activity for any geotechnical project. The Ground model is an essential tool for engineering quality control and provides a transparent way of identifying project-specific, critical ground and groundwater risks and properties.

Any Ground Model must consider the zone of influence (ZOI) since they are intrinsically linked. The zone of influence should be defined at the same time as the Ground Model is first considered. The importance of this is discussed in 2.2.

The following aspects should be reported regarding the selected zone of influence:

- The location and type of geotechnical structure(s) that is the origin of the ZOI.
- Potential construction methods considered.
- Considerations that have influenced the selection of the zone of influence.

Figure 1 shows the transition from the Ground Model to geotechnical design model. Although not shown in this figure, it is implicit that the Ground Model is developed alongside the Ground Investigation Report (GIR) and indeed much of the data accumulated in the GIR will help to inform the Ground Model.

When the Ground Model has been included in the geotechnical design model, it serves as a base to estimate (and if possible, quantify) the effects of the planned activities on the surrounding area. These effects could pose significant financial (and time) risks if additional constraints arise too late in the project. Similarly, the Ground Model as part of the geotechnical design model should aim to estimate (and if possible, quantify) the effects of existing land use on the surrounding areas for the same reason.

The Ground Model is linked to the corresponding Ground Investigation Report to track in time, localise in space, justify the investigation choices, and allow the designer an easy method of consultation and/or interpretation of all the results obtained from the surveys.

2.2 Zone of influence

The zone of influence (ZOI) for any geotechnical structure is defined in EN 1997-1:2024, clause 3.1.6.1. In relation to the Ground Model (GM), the ZOI must be considered integral when assessing the scope of the Ground Model. In other words, the area of ground covered by the Ground Model is to be the same as the ZOI.

The selection of the zone of influence is crucial to evaluate the effects of the planned activities on the surrounding area as these might pose considerable financial (and time) risks if additional constraints appear too late in the project. The aspects listed in the bullet points in section 2.1 must be considered when identifying the zone of influence.

It is a common error to make the ZOI too small to cover all the potential actions that new structures may cause to surrounding areas and/or structures and equally too small to include all the actions that surrounding areas and structures may have on the proposed design structures.

For the proposed structure(s) it is straightforward to determine the likely influence zone produced by the structure's foundations and related noise and vibrations, whether these are simple spread footings or a deep pile group. It is also reasonably straightforward to determine these effects for sheet piling and excavating a deep basement on the surroundings.

It is more complicated, however, to assess other effects caused by the new structure(s). Such effects might be dewatering, whose zone of drawdown might extend several hundred meters beyond the structure itself and hence affect surrounding areas and/or structures that block groundwater flow. Such potential effects will, however, need to be included in the ZOI. The same considerations would apply to ground freezing or the placement of long soil nails, anchors, rock bolts, etc., that extend into the surrounding ground.

When determining the ZOI and area to be included in the Ground Model, careful consideration of the planned and possible construction techniques must be undertaken.

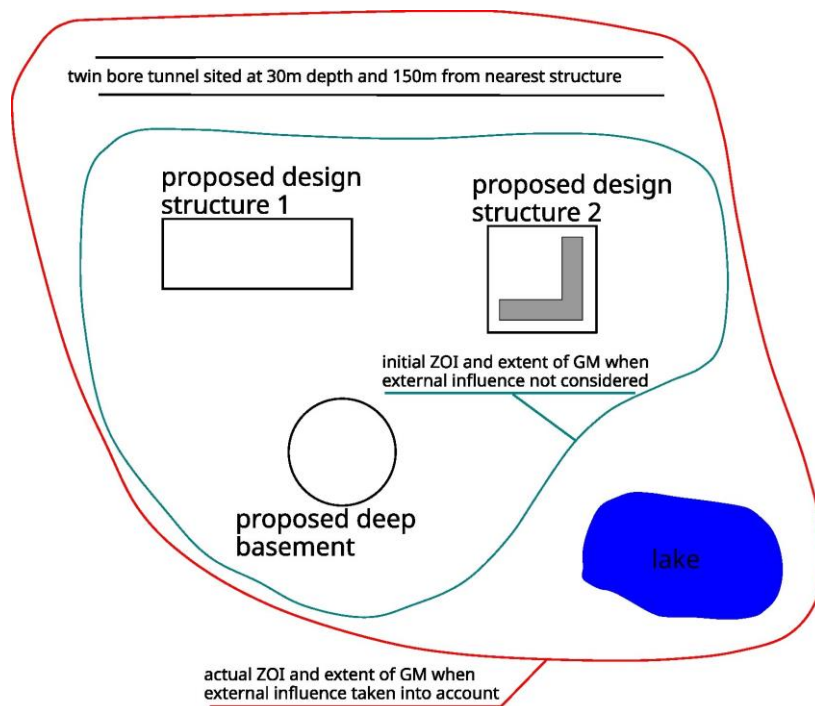
Similarly, for areas and/or structures that surround the site, their potential impact on the structures to be designed must also be considered. For example, existing land that contains large bodies of water (reservoirs, lakes, etc.), areas of contamination or other hazardous ground, must be considered within the ZOI, if it is considered possible that these could impact on proposed structures. Existing structures with deep piled foundations may impact the site, insofar as the existing pile group ZOI may overlap with that of the proposed structures. Similarly, activities with cyclic loadings may have to be considered if they would impact the proposed structures.

Based on the comments above, it can be seen that the ZOI and Ground Model are closely linked, and when assessing the scale of ground (site area) to be considered for inclusion, careful consideration must be given to the geotechnical proposals. This is especially important since the scope of the ground investigation will be based on the extent of the ZOI.

In the same way that it is a common mistake to make the ZOI too small for the site, so the scope (lateral extent) of the Ground Investigation (GI) is often too small. The correct sequence, as given in EN 1997-1:2024, is to identify the ZOI included within the Ground Model and then assess the scope of the GI that needs to be carried out to provide all design information.

The importance of considering the true extent of the ZOI is shown in Figure 2. This shows a site on which three structures are proposed. Just considering the structures themselves without any external influences would result in the ZOI shown in blue. However, when the possible effects of the existing tunnel and lake are taken into account, it can be seen that a larger ZOI shown in red is required. This in turn, would lead to a more extensive GI being undertaken. In particular, the depth of investigation will be influenced by the need to pile any foundations and on the level of the tunnel and the depth of the base of the lake.

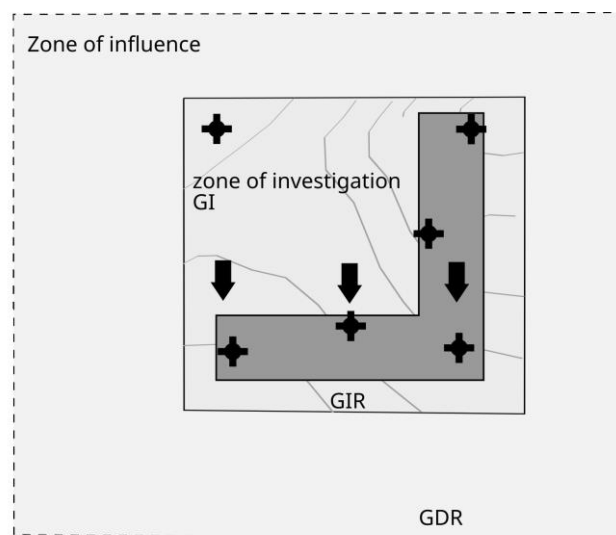
Figure 2. The importance of correctly identifying the ZOI in relation to both proposed and existing structures.



Source: Authors' own work.

In Figure 2, the initial assumption for the ZOI ignoring external influences is shown as a blue line. However, when all possible external influences are considered, the ZOI is extended as shown by the red line.

Figure 3. Importance of correctly identifying the ZOI in relation to a single structure.



Source: Authors' own work.

In Figure 3, the extent of the ZOI when only a single structure is considered in isolation as part of the Ground Investigation Report is shown by the solid black line. When all design issues are

considered however as required in the Geotechnical Design Report (GDR), the target area for the ZOI and hence that of the GI increases considerably. The revised ZOI is shown by the dotted black line.

2.3 The extent of the Ground Model

It is critical to the success of any project that the extent of the Ground Model is appropriate to the project and the ground and groundwater conditions. Whilst the complexity of the Ground Model will vary depending on the phase and nature of the project being considered, in every case, the Ground Model should match the zone of influence that has been identified as relevant to the project as a whole (see 2.2).

Initially, as noted in EN 1997-1:2024 4.1.2.1 (4), the extent of the ZOI and, by extension, the extent of the Ground Model, is to be estimated before planning the ground investigation. It is anticipated that this can be achieved by undertaking a desk study and site inspection, ensuring that the correct extents of the ZOI and Ground Model are identified. Figure 3 shows that an initial assessment of the extent of the required Ground Model (and hence the zone of influence), based only on the structure is likely to underestimate the required extent. Consideration of external influences may well increase the extent of the Ground Model, and this is illustrated by the dotted line as compared to the initial inferred extent that is shown by the solid line in Figure 3. In other words, the effective area of influence of the structure can be larger than what is often understood to be the 'site'.

As the design process for the project proceeds, and in particular, for large complex projects, sections of the Ground Model may require more detail or a 'zooming in' with respect of the amount of data required to understand the ground and groundwater. This will help to:

- avoid starting with a too narrow perspective and having to make fundamental design changes later in the process, which might pose unexpected problems and delays,
- being able to target areas where you need additional data to reduce uncertainties.

For this reason, it is possible that for large and complex design situations, although there may be one overarching Ground Model, subsets of more localised Ground Models focussing either on individual structures (or parts of structures), or on specific areas of the overall ZOI that require more complex modelling, may be prepared as the design progresses.

For linear infrastructures like railways, metro lines, dikes, etc. alternative ways of presenting the Ground Model may apply, such as a 2D section along the structure.

One part of the Ground Model and by extension the ZOI is the area where construction works, or the geotechnical structure can adversely affect the safety, serviceability, robustness, durability, or sustainability of the geotechnical structure itself and of other structures, utilities, ground, groundwater etc. The other part of the Ground Model (and ZOI) that needs careful consideration, is that of the nearby surroundings that can affect construction works or the geotechnical structure itself.

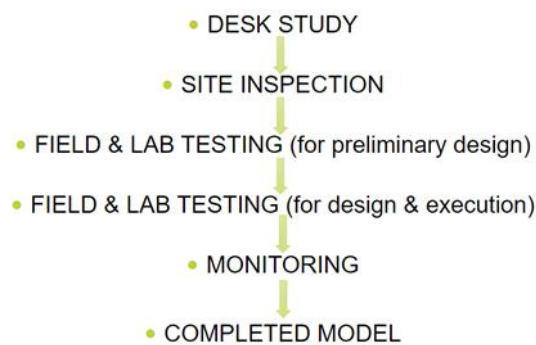
The geographical extent of the Ground Model varies not only in relation to geotechnical works or geotechnical structures but also with regard to the anticipated design situation, and also in relation to seismological features. Where seismicity is known or suspected, this must be considered in the overall design process. In such cases, the link between Ground Model and ZOI becomes less important due to the extreme geographical extent of seismic phenomena. Similarly, the extent (vertically) of any ground investigation, must take into account the effects of seismicity.

The extent of the zone included in the design ground investigation plan for a geotechnical structure might be reduced in scope compared to that covered by the Ground Model and overall ZOI.

2.4 Stages

It is advisable to update the Ground Model at each key stage described in the EN 1997-2:2024 and which is reproduced in flow chart form in Figure 4. The stages of development of the Ground Model should be corresponding to the Geotechnical Category and in particular, the Geotechnical Complexity Class in which the ground is classified as the level of detail increases.

Figure 4. Key Stages for the development and updating of the Ground Model.



Source: Authors' own work.

It is possible to identify several critical stages where the Ground Model should be assessed and updated as necessary. Whilst the development of the Ground Model is an ongoing activity that will last for the life of the project, the stages shown in Figure 4 are clear milestones at which additional data should have been gathered and the model reassessed.

A preliminary version of the Ground Model must be prepared at the desk study/site inspection stage. This will comprise topographical, geomorphological, geomechanical and stratigraphical information obtained from available maps or previous survey campaigns. The preliminary model will allow for the optimising and planning of site and/or laboratory geotechnical investigations and their concentration where needed, ensuring a level of detail and a spatial extent of investigations appropriate to the area of influence of the structure. Subsequently, it will be improved iteratively as data are collected.

After investigations are carried out for the preliminary design, the Ground Model should present the geotechnical, hydraulic, and hydrological features of the different Geotechnical Units that form the ground. This detailed representation allows for an accurate evaluation of the various typologies of structures, the risks associated with construction, the potential construction and risk mitigation techniques, and the organisation of the work and its associated costs. Furthermore, the Ground Model must include all the ground elements that are essential for the preliminary design phase.

For the final design, additional and more advanced testing is included, as appropriate, with consideration given to the needs presented in the corresponding geotechnical design model. The geometrical, geotechnical, and hydrological features of all the Geotechnical Units must be presented with enough detail to make the final design of structures and to confirm the risk scenarios and mitigation strategies identified in the preliminary design. Finally, monitoring will

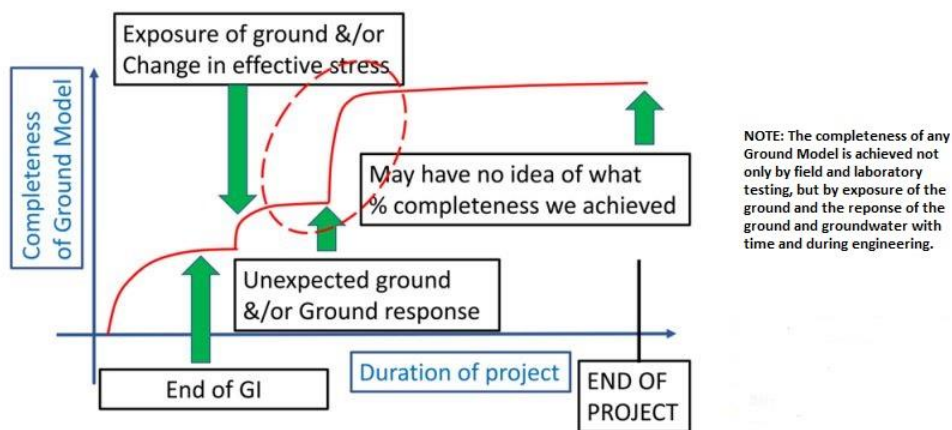
depict any temporal variations in certain variables, such as groundwater level, weather conditions, and seismicity, in the final Ground Model.

2.5 Development during the project

It is expected that the Ground Model will be developed and take into account various data sets accumulated as investigation and knowledge increase during the project's progress.

It is also essential to recognise that the development of the Ground Model will not necessarily be a gradual accumulation of ground data. Various factors may impact on the completeness of the Ground Model, as shown in Figure 5.

Figure 5. Ground Model development during the project.



Source: De Freitas (2021)

In Figure 5, the ongoing development of the Ground Model is shown. At the end of the initial ground investigation, a certain amount of data on ground and groundwater conditions has been accumulated. However, when construction commences and the ground is exposed, the response of the ground may differ from that predicted, so the model is further refined and updated. In the longer term, monitoring for example may produce additional data that indicates the need for further updating of the model.

Risk and risk control are key elements in any project's costing. In general, the lower the amount of risk that can be tolerated for a project, the greater the project's cost. Also, uncertainties regarding ground conditions lead to costly necessary safety measures in design. For this reason, the incorporation of risk and its relationship to the Ground Model is essential and should be considered in the model's development, as shown in Table 1.

Regarding the Ground Model, during the design process, the objective is to reduce the risk-related costs concerning the ground conditions. Therefore, the requirements for each phase regarding the accuracy and acceptable uncertainties are derived from a cost-based analysis of geotechnical risks resulting from uncertainties versus construction costs. This objective must be clearly defined before the start of a Ground Investigation for each phase to verify whether these objectives have been met.

Table 1. Relationship of Risk to the Ground Model development.

The process	The Ground Model	Risk	Financial profile
STAGE 1A: STRATEGY FOR DESIGN	BASIC GROUND MODEL (1)	INITIAL RISK	INITIAL FINANCIAL CONSEQUENCES
Proposed structure, existing information, experience, known geology	A basic Ground Model is developed.	Will always be high initially due to the number of unknowns.	Initial risk-related costs will always be high due to the number of unknowns....
Initial strategy for geotechnical design	Any assumptions on the ground & groundwater added	RISK = HIGH	
STAGE 1B: STRATEGY FOR DESIGN	BASIC GROUND MODEL (2)		
Site inspection	Surface features added.	Site inspection and full desk study are the first steps to reducing the risk	The first step to reducing risk-related costs
Enhanced strategy for geotechnical design	Further development of the Ground Model	RISK = HIGH/MEDIUM	
STAGE 2: GROUND INVESTIGATION	DEVELOPED GROUND MODEL		
Planning and re-evaluation of the investigation programme	Results of all phases of the geotechnical investigation work(s) are added to the Ground Model	Undertaking a Ground investigation appropriate to the complexity of the structure will significantly reduce the level of risk from the unknown ground and groundwater conditions.	
Field investigations (testing and sampling)	Ground & groundwater information added, together with seismic properties for ground response analysis	A more accurate Ground Model = more accurate input to the GEOTECHNICAL DESIGN MODEL	Verification of Ground Investigation reduced risk-related costs to a pre-defined level for the project phase
Laboratory testing	Ground properties		
Reporting	Where required a full 3D model is produced		
STAGE 3: DESIGN			
Ground model is developed with the addition of design data into the geotechnical design model	Transition into the GEOTECHNICAL DESIGN MODEL	RISK = MEDIUM/LOW	Ground model is developed with the addition of design data into the geotechnical design model

Source: developed by the authors

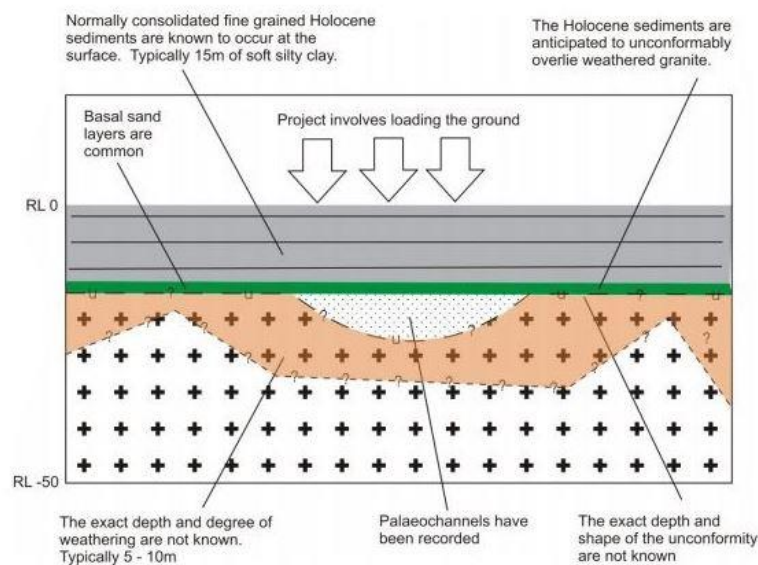
2.6 Method to assemble the Ground Model

The method of assembling the Ground Model will depend on the complexity of the project. For straightforward structures that classify as GC1 structures in EN 1997-1:2024, it may be possible and desirable to restrict the GM to an elementary sketch diagram with a few key ground descriptors incorporated.

For GC2 and GC3 structures, more complex Ground Models will be required. In some cases where large and complex structures are being constructed, separate more localised models may be needed to show information for specific sections or areas of the ground.

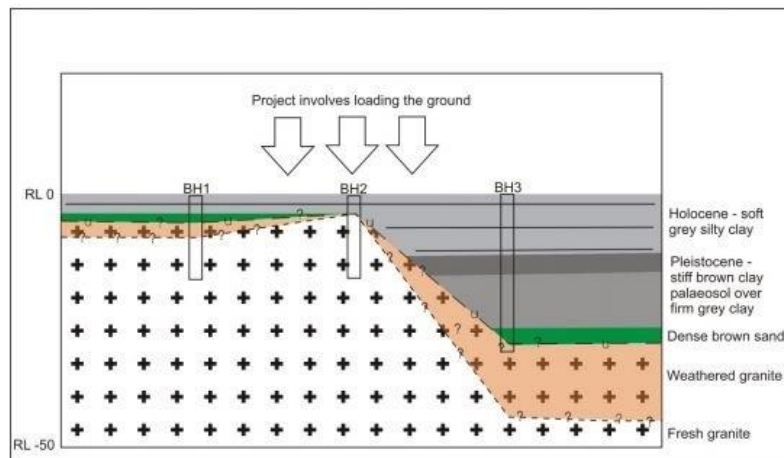
In all cases, the model may be built up by a series of increments as information on the ground is obtained (see Figure 6 and Figure 7).

Figure 6. Initial Ground Model based on a desk study and site inspection information.



Source: Parry et al. (2014)

Figure 7. Ground Model developed to include information from the ground investigation.



Source: Parry et al. (2014)

2.7 Complexity and Geotechnical Category for the Ground Model

It is vital for any project that the Ground Model be directly related to the Geotechnical Category of the structure and the ground, for which the design is being undertaken.

As noted previously, it might be reasonably expected that the complexity of the Ground Model will increase with the increasing Geotechnical Category. In other words, a Ground Model produced for a GC1 structure is likely to be simpler than a Ground Model produced for a GC3 structure.

For each of the key project stages recognised by EN 1997-1:2024, consideration of the Ground Model content should be assessed relative to the Geotechnical Category. Table 2 gives a simple overview of this relationship.

For complex and multiple structures within a single project, it is expected that even though there might be a single over-arching Ground Model, multiple smaller (subset) Ground Models may have to be produced. A single overview Ground Model of the whole ZOI might be accompanied by other Ground Models relating to the specific parts of the site and/or specific structures.

Where multiple subset Ground Models are to be generated, it is recommended that these are documented or listed in such a manner that they can be checked against the complexity of the structures and assessed for their adequacy. It is equally important that they can be referenced to and within the main over-arching Ground Model for ease of use.

It is important to note that Table 2 is only intended as a prompt for the designer so that at each stage of Ground Model development, due consideration can be given to assessing what information should be added to the model.

In terms of the types of Ground Model that might be produced, Table 3 gives some onward reference for examples, although it should be recognised that the range and complexity of models that might be produced for a project are very extensive.

Table 2. Simplistic linkages of the Ground Model to the Geotechnical Category

Geotechnical Category GC	Development of Ground Model with the life of the project					
	Desk Study (Key stage 1)	Site Inspection (Key stage 2)	Field test & laboratory testing for preliminary design (Key stage 3)	Field test & laboratory testing for design & execution (Key stage 4)	Monitoring (Key stage 5)	Fully developed Ground Model
	→ Key elements used in the building of the Ground Model →					
GC1	All items in GC3 considered?	May be done at the time of GI? A 'skilled eye' inspection is required	GI undertaken if necessary	Simple GI. Minimum for the type of structure	Not required	SIMPLE COMPLEX GM (see example Table 3)
GC2	All items in GC3 to be considered	All items in GC3 to be considered	May be required depending on	GI appropriate to the type of structure	Displacement gauges Inclinometers	MEDIUM COMPLEX GM

Geotechnical Category GC	Development of Ground Model with the life of the project					
	Desk Study (Key stage 1)	Site Inspection (Key stage 2)	Field test & laboratory testing for preliminary design (Key stage 3)	Field test & laboratory testing for design & execution (Key stage 4)	Monitoring (Key stage 5)	Fully developed Ground Model
			the type of structure and how complex the ground is		Piezometers, etc., if relevant	(see example Table 3)
GC3	Topography Geology Hydrogeology Seismicity Archaeology Site condition Land Use Local and prior knowledge Codes, standards	Skilled 'eye' inspection of site soil & rock outcrops Marsh, peat Standing water Pits, hollows, shafts vegetation	Good practice to undertake some basic GI to inform design before the main GI work is undertaken	One or more phases of GI are undertaken to produce sufficient information on the site conditions	A full range of monitoring types used. To include ground and groundwater movements	COMPLEX GM (see example Table 3)

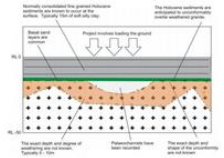
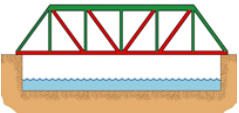
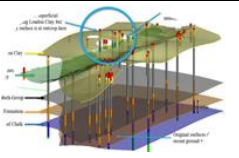
Notes:

- Development of the Ground Model is a continually evolving process. It should not be considered complete until items in all five of the key stages listed in the table have been assessed.
- Where the Observational Method is employed, monitoring (Stage 5), will be of critical importance.
- For simple GC1 structures, key stage 4 may not be required as all field tests and lab testing, etc., for design will be completed within key stage 3.
- If groundwater conditions are relevant for a project and the desk study has shown that suitable time series for groundwater levels are not available, groundwater monitoring should commence in phase 3.
- GM = Ground Model, GI = Ground Investigation

Source: Authors' own work

Table 3. Summary of examples of Ground Model types linked to development and ground complexity.

Model Complexity No	GC	Description	Examples	Ground Model type	Model example
1	1	Simple structure CC1 on uniform ground conditions. Incompressible soil or rock	Domestic dwelling or small commercial warehouse. Construction on stiff clays / dense coarse soil / >mod weak low fractured rock mass.	Written text describing the ground and interaction of the structure	Single house Strip footing at 1.0 m depth Stiff clay from 0.5 m to 10 m Water table >10 m depth No external influences

Model Complexity No	GC	Description	Examples	Ground Model type	Model example
2	1 to 2	Simple structure CC1 on more complex / multi layered soils / fractured / weathered rock, etc.	Domestic dwelling, or small commercial warehouse. Construction on <stiff clays, <dense coarse soil, < medium strong low to medium fractured rock mass	A simple diagram showing the structure and anticipated / known ground conditions	 Source: Parry et al. (2014)
3	2	More complex structure (s) CC2 on uniform ground conditions.	Commercial warehouse, factory, bridge etc. Construction on <stiff clays, <dense coarse soil, <med strong low to medium fractured rock mass.	2D or 3D drawings detailing structure(s) and associated more complex foundations and their interaction with the ground	 Source: Authors' own work
4	2 to 3	More complex structure(s) CC2 coupled with more complex ground conditions. Compressible / multilayered soils / fractured / weak rocks, etc.	Factories, large bridges, ports, stations, and struct. with deep excavated basements. Construction on mixed fine and coarse soils, weak and/or complex fractured rock mass. High water table.	3D drawings or drawings showing all foundation interactions with different material types	 Source: Ting, Gilson and Black (2020)
5	3	Very complex CC3 structure(s) coupled with complex ground conditions.	As in 4 above, but also includes nuclear developments and other structures having complex foundations/minimal tolerance to settlement/very high foundation loads.	3D drawings showing all foundation interactions with different material types. Separate model drawings for different structures / different / complex foundations	-

Source: Authors' own work

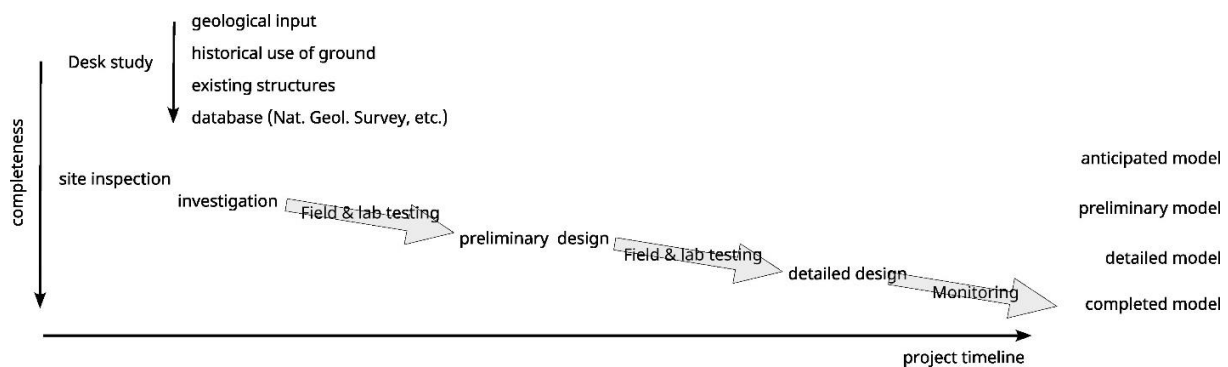
In Table 3, the consequence classes (CC), as defined in EN 1990:2023, have been added in column three to provide a link to the definitions given in Part 1.

3 Input bases for the Ground Model

3.1 General

The inputs for any Ground Model are likely to be acquired over a period of time. This period will depend on the complexity of the ground and groundwater conditions within the area under consideration, as well as the construction. Irrespective of the period, the inputs to the GM are likely to be obtained at some or all of the key stages shown in Figure 8.

Figure 8. Key Ground Model input stages during the life of a project.



Source: Authors' own work.

Within each key stage noted above, the Ground Model should be formed of both the known and anticipated geological, geomechanical, hydrogeological and geotechnical conditions at, under, and around the site, e.g. in the zone of influence (ZOI). As noted previously, the ZOI should be ascertained at an early stage during the life of the project but may change in scope as proposals for structure(s) are refined or changed. It is stressed, that an accurate understanding of the ZOI is key to ensuring that all inputs that may be relevant to the Ground Model are considered.

Key inputs are described below:

- geological conditions, including, but not limited to the description of the site geomorphology, the lithology of the geotechnical units, the potential presence and level of geometrical and physical properties, orientation of discontinuities, and weathered zones, and the rock mass classification;
- geomechanical conditions, such as preliminary assessments of in situ stresses, stiffness and strength;
- hydrological conditions address surface, groundwater and piezometric levels, which include their potential variations with time and the presence of other fluids or gases affecting the site;
- seismological assessment for the wider area needs to be undertaken at an early stage;
- geotechnical characteristics including but not limited to such aspects as the disposition of the geotechnical units and the mechanical behaviour of the ground and discontinuities, described through the geotechnical properties of the geotechnical units.

When gathering the data, comparison of the data on the same platform for environmental, geomechanical, and hydrogeological data is very important to allow the different members of the design team to evaluate the interactions with the projected geotechnical structure.

Data sources include but are not limited to:

- cartography, topography, Digital Terrain Model (DTM);
- geological maps and geological databases: subsoil database (from national geological survey);
- hydrogeological maps, water tables;
- risk maps, if any: floods, earthquakes, slope instability, swell-shrinkage susceptible soils;
- bibliographic and historical data related to excavation works, tunnels, historic land use, etc.;
- general investigation data for geological and hydrological models and specific investigation data for the geomechanical properties, together with data specific to earthworks and foundations, etc.;
- environmental data: protected flora and fauna, species, natural routes, legislation for water protection and drilling codes, if any etc. Indeed, the European Environmental Code stipulates that "programs or projects for works, structures, or developments subject to an administrative authorisation or approval regime, and whose implementation is likely to have a significant impact on a protected site, are subject to an assessment of their impact with respect to the site's conservation objectives".

Finally, the Ground Model should include the derived values of the relevant ground properties for all the geotechnical units encountered in the zone of influence.

3.2 Initial input considerations

Based on an initial understanding of the ground and groundwater, the project, and the type of construction, some initial assumptions regarding the size and complexity of the Ground Model may be constructed. Three levels may be considered: general/overview, systematic and detailed as shown in Table 4. These will help inform the type and quantity of input parameters for the Ground Model.

Table 4. Types of Ground Model complexity and their characteristics

Aspect of the model	Overview Model	Systematic Model	Detailed Model
Cross-section spacing	Several hundred m	50 – 150 m	< 50 m
Density of investigation points	< 1 per km ²	Commonly 5-20 per km ²	According to EN 1997-3
Depth of investigation points	-	-	According to EN 1997-3
Geophysical Methods	Rapid general 'scans'	Focussed analysis	NA
Stratigraphical level	Major Groups and Formations only	Formations and Members; big lenses, artificial ground (Reclaimed areas, filled areas, ... with thickness >1m)	Members and thin individual beds and lenses; artificial ground
Modelling speed (excluding data preparation)	Up to hundreds of km ² per day	2-10 km ² per day	< 2 km ² per day
Scale	Compatible with 1:625000 and 1:50000 geological linework	Compatible with 1:25000 and 1:10000 geological linework	Compatible with detailed site plans at scales as large as 1:1000
Minimum unit thickness	2 m	1 m	0.1 m
Modelling output	Often, only sections and an open fence diagram	Computation of surfaces for export to GIS	Computation of surfaces and lenses for export to GIS
Uses	Education, visualisation and overviews (for example, general catchment characterisation), first-pass assessments		

Source: Authors' own work.

It should be noted that one or more of the above types of Ground Model may be required. It may be necessary for example to have a general 'overview' model for the project, as well as one or more systematic/detailed models to illustrate different structures or parts of structures. Such requirements are likely to become clearer as the project proceeds.

By making use of the key stages shown in Figure 8 it is possible to identify some key items that should be considered as each stage is reached. Whilst not being an exhaustive list, these examples are shown in Table 5.

Table 5. Example Ground Model input considerations for different stages of the project

Stage	Group	Details
Desk study (1)	Objective	What is going to be constructed and establish ZOI
	Existing objects within ZOI ⁽¹⁾	Cables / pipes / sewerage / structures / objects / buildings / foundations / backfilling / excavations /... — (as-built) Drawings — Design reports — Geotechnical parameters used in the design
	Historical data of the ZOI	Aerial photographs Topographic maps/surveys Hydrographic maps/surveys Historical maps Archaeological studies CTE/UXO
	Geological data of the ZOI	Geological maps Geological description of the existing soil and rock layers
	Hydrogeological data of the ZOI	Existing groundwater monitoring, groundwater analysis and investigations (sludge tests, pumping tests, piezometers, ...) Hydrogeological maps Hydrogeological description of the existing soil and rock layers
	Geotechnical data of the ZOI	Existing ground investigation (in-situ & laboratory) Geotechnical parameters used in previous designs
	Ground contamination and groundwater contamination within ZOI	Existing ground investigation
	Uncertainty	Start an assessment of uncertainties and risks to help reduce financial and other impacts during construction. Basis for field investigation and lab testing.
Site Inspection (2)	Photographs (including the location of the photograph) Elaborate report, based on a skilled 'eye' inspection of the site, soil and rock outcrops, marshland, peat, standing water, hollows and surface depressions, shafts, vegetation types, and existing structures. Start an assessment of any uncertainties that need to be addressed by future investigation.	

Stage	Group	Details
Field and laboratory testing (3)	Preliminary Design	Check ZOI and key parameters required for Ground Model to define required ground investigation (soil, rock and groundwater)
		Check ZOI and key parameters required for Ground Model to define required laboratory testing (soil, rock)
	Monitoring equipment	Install monitoring equipment to enable baseline measurements to be started. (NB this could be done at an earlier stage if necessary)
	In situ investigations and laboratory data	Make use of all ground data and test results to help refine initial ground units in the GM. Start 3D input to Ground Model
	Uncertainty	Update assessment of uncertainties and risks to help reduce financial and other impacts during construction
Field and laboratory testing (design) (4)	Main design	Check ZOI and key parameters required for Ground Model to define required ground investigation (soil, rock and groundwater)
		Check ZOI and key parameters required for Ground Model to define required laboratory testing (soil, rock)
	Monitoring equipment	Install monitoring equipment. If not done previously, commence baseline measurements. (NB this could be done at an earlier stage if necessary)
	In situ investigations and laboratory data	Make use of all ground data and test results to help refine initial ground units in the Ground Model. Start 3D input to Ground Model. NB if stage 3 is not carried out, the information obtained here will be used as the main method of refining the initial Ground Model.
	Uncertainty	The level of detailed information obtained at this stage will be the most important tool for helping to define uncertainties / risks and this in turn will help reduce financial and other impacts during construction
Monitoring (5)	In situ and remote	Analysis of time series monitoring data to help confirm / improve the characteristics of the Ground Model units
		Make use of data series to help recognise uncertainties / risks
Future project (6)	Where projects are to be undertaken at some time in the future and stages 1 to 5 above have not been undertaken, the following information should be obtained and analysed when considering initial inputs for the Ground Model: — Drawings — (preliminary) design reports — Timing — Execution methods (excavations, shallow and/or deep foundations, driving, GW-lowering, ... — Extent of ZOI	

Source: Authors' own work

3.3 Geological input

All Ground Models should start with the designer's initial thoughts on the soil and/or rock units that might underlie the ZOI, together with initial groundwater considerations. This initial Ground Model input may be derived from knowledge held by the designer relating to ground conditions in the area. Alternatively, the initial input may be derived from geological maps, previous investigations, together with a site visit.

The input data may be transformed into a drawn two-dimensional (2D) or three-dimensional (3D) model; or for very simple structures could be in the form, of a written model that describes the anticipated geological units.

The importance of an early appreciation/assumption of the likely geological conditions within the ZOI cannot be overstated. Many of the following design decisions and indeed strategy for the physical intrusive ground investigation, will be directed, by these early Ground Model inputs.

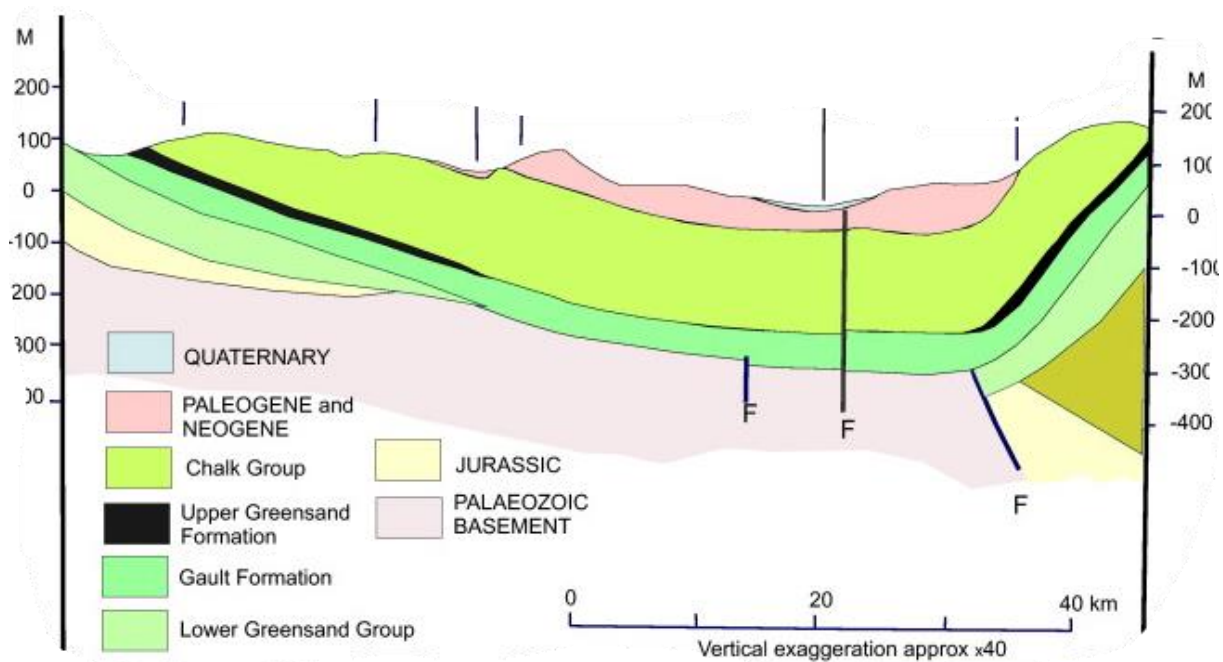
Table 6 and Figure 9 show two examples of Ground Models, developed at an early stage. The first (Table 6), for a single house, comprises a tabular geological assessment; this comprises the extent of the geological input. The second (Figure 9), is more complex and shows the anticipated geology based on maps and other existing information. Neither include any information that would come from intrusive field investigations.

Table 6. Example of tabular style Ground Model for simple structure formed before any GI has taken place.

Geological unit	Likely depth	Comments
Anthropogenic ground	Absent to a maximum of 2.0 m?	Part of the site was used as an iron foundry.
Alluvium	G.L to a maximum depth of 5.0 m	Probably some soft clays and silts are present.
Glacial sands and gravels	2.0 / 3.0m depth, extending to 10.0 m	Local gravel pit records and inspection indicates that these deposits comprise fine to coarse sands and fine to coarse gravel with some cobbles.
Rock (weathered carboniferous sandstone)	Variable but unknown depth. Possibly as shallow as 7.0 m	The map shows fine grained sandstone.
Groundwater	Probably present in Glacial deposits	The river is 150 m from the site. Need to check hydraulic conductivity via monitoring.

Source: Authors' own work.

Figure 9. Example of simple geological GM formed before any GI has taken place.



Source: Banks et al (2015)

Defining the units should be carried out using the description classifications given in EN ISO 14688:2017⁴ (soil) and EN ISO 14689:2017⁵ (rock).

3.4 Historical use of ground

The historical use of the land is more generally examined as part of the desk study (old historical charts, records or maps, aerial photography, etc.) to prepare an investigation strategy. However, the site visit can give vital information and/or clues on the former site use. For example, surface depressions, voids, discoloured soils, artificial soil, and rock exposures can all point to human activity on the site, both at the surface and possibly at depth (see Figure 10).

Available historical, geological, geotechnical, environmental, and hydrogeological data are of vital importance when constructing a simple Ground Model as well as for a 3D Ground Model. From maps and plans, information that can be listed includes:

- Anthropogenic ground, fill, brownfield;
- Old mining pits or quarries for stone, lime, plaster, etc. Following the cessation of quarrying operations, sites were often only partially filled with inert material and capped with topsoil before the 'gates closed';

⁴ EN ISO 14688:2017 *Geotechnical investigation and testing — Identification and classification of soil, Part 1: Identification and description* and *Part 2: Principles for a classification*, International Organization for Standardization ISO, 2017.

⁵ EN ISO 14689:2017 *Geotechnical investigation and testing — Identification, description and classification of rock*, International Organization for Standardization ISO, 2017.

- Hydrogeological information such as old pumping systems that have lowered the groundwater table for decades during the 19th century, old pollution, and alluvial formations defines a hydrogeological model to analyse the very-low-energy geothermal potential of a specific area.

Figure 10. Examples of the historical use of ground requiring inputs to a ground model.



a) Buried Shaft.



b) Ancient tunnels beneath site.



c) Surface contamination.



d) Surface collapse above chalk mines.

Source: A); B) ©M. Baldwin, 2015; C) ©M. Baldwin, 2012; D) Cooper, Farrant and Price (2011)

3.5 Existing structures of remaining substructures

It is common, particularly in urban areas, for new construction projects to take place on sites or areas of land where there has been previous building. Often, such previous structures can be dated within the past 200 years, but there are occasions when much older structures are present.

In all cases, careful consideration of available maps and plans should be undertaken to ascertain the likely extent of such structures, both at ground level and also in respect to buried elements of the original buildings. In some cases, this will involve careful excavation to reveal the lateral and vertical extent of the original structural elements. Interaction with archaeologists may also be required depending on the age and nature of the previous structures.

It should also be noted that it is possible to detect buried foundations and pipelines, etc., by means of geophysics and simple ground-penetrating radar (GPR).

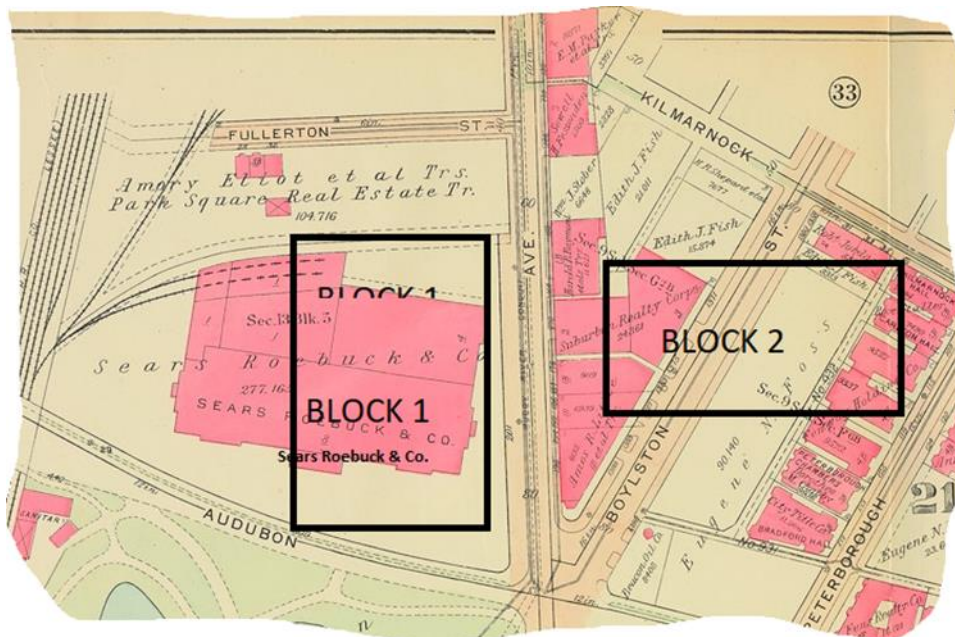
With regard to possible inputs for the Ground Model, consideration should be given to hidden infrastructure, e.g. foundations (timber piles from buildings, piers, etc.), cables, pipes, tunnels, and

potential archaeological finds. But also, war remains such as trenches (for example, those from World War 1), dangerous artefacts, underground construction, bunkers, etc.

Again, a combination of available historical, geological, geotechnical, environmental & hydrogeological data is vital for locating these hidden structures. In particular, the use of aerial reconnaissance (perhaps using drones) can provide a good overview of the overall site and/or ZOI.

Figure 11 shows a historic buildings plan on which the outline of two proposed structures (Blocks 1 and 2) are shown. Historic structures will impact on the new structures and this information should be added to the Ground Model.

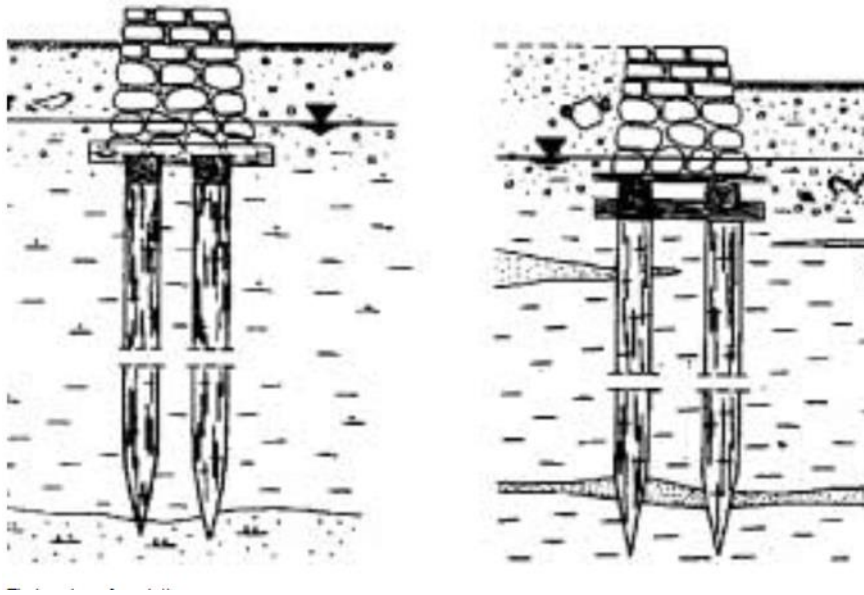
Figure 11. Use of historic plans to assess existing structure impacts on construction.



Source: Geo. H. Walker & Co. (1895)

At a more detailed level, having identified that historic structures might impact the new structures, it may be possible to access foundation records. An example of old timber foundations is shown in Figure 12.

Figure 12. Old timber piles revealed by analysis of historic building plans.



Source: Przewłócki, Dardzinska and Swinianski (2005)

The information shown in Figure 12 would clearly be important for the Ground Model of new structures. Not only is the extent of a potential obstruction shown, but some limited information on geological units is given on the original plans and this can be added as an input to the new developing Ground Model.

Where known or suspected, the presence of former structures, both on the surface as well as below ground, should be added to the Ground Model. The more detail that is added at an early stage, the better informed will be the subsequent GI strategy.

For sites or ZOIs where there has been a complex history of former buildings/land use, it may be necessary to construct a separate 'existing structures' Ground Model. Ideally, this should be overlaid on the anticipated geology so that the likely existing interaction of demolished or partly demolished structures can be assessed.

3.6 Input from the investigation database available in ZOI

Once information regarding the types of structures and their associated foundations is known, more specific inputs for the Ground Model can be considered. In particular, values associated with specific foundation types should be considered as should cases where foundations will interact with adjacent foundations.

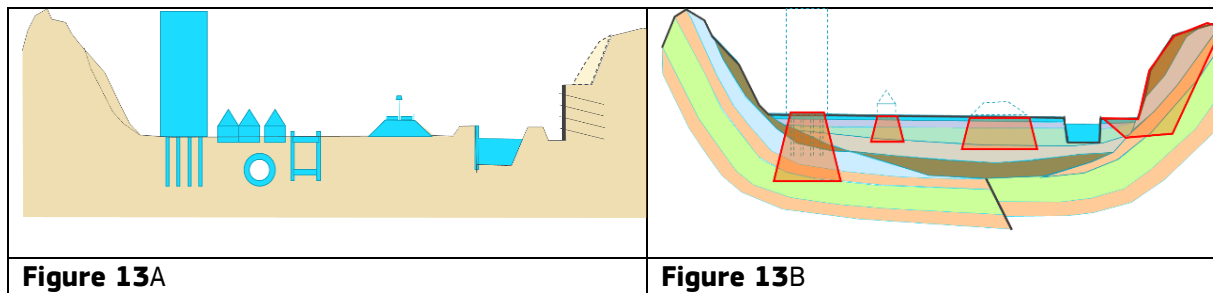
For most projects, it is accepted that at a preliminary stage of a project, the Ground Model will require to be extended or modified as data is acquired. The desk study will have a draft description of the structure and soil, rock, and groundwater structure interaction principle achievable. At each project stage, the zone of influence may be modified according to the geotechnical structure planned.

The influence of seismic actions on the ZOI cannot be easily generalised. For structure footings, the ZOI will be less than the static case and in any case such actions should not be considered within the Ground Model, since the geotechnical design model (GDM) will deal with these. Where seismicity

needs to be taken into account, it is more useful to ensure that the Ground Model is sufficiently extended to cover the ground potentially giving amplification effects during earthquakes.

Figure 13 shows the proposed structures for a particular project. In Figure 13A, the proposed structures have merely been input onto a 'blank' Ground Model. In Figure 13B, the structures and their anticipated foundation loadings in terms of the ZOI are shown superimposed on the expected geology. By knowing or at least anticipating the location of structures in relation to expected geology, it is possible to better plan the Ground Investigation.

Figure 13. Principle of defining the zone of influence according to the type of structure.



Source: Authors' own work.

For most projects, the approximate locations of structures are known at an early stage. It is therefore important to add this information to the Ground Model. By the time this information is added, the Ground Model should comprise the following elements/input data:

- Geological information (Soil and Rock)
- Hydrogeological information
- Historical land use
- Existing structures/substructures

There is guidance available regarding the ZOIs for different types of structures and their associated foundations. A summary of this information is given in Table 7.

Table 7. Preliminary contributions to the ZOI according to geotechnical structures as in Eurocode 7 Part 3.

Area to be considered		Case	Horizontally	Vertically		
			L_{min}	d_{min}		max
				GC1	GC2	
Slopes		a		2 m	max (0.4 x H; 3 m)	
Cuttings		b			max (0.4 x H; 2 m)	
Embankment, dike		c		2 m	3 max (1.2 x H ; 1.0 x B ; 3 m)	1.2xH
Spread foundations	isolated	d		2 m	max (3.bf ; 3 m)	
	raft	e			max (3.bf; 6 m)	
Piled foundations	single	f			max(>3.B; 5 m)	
	Pile group	g			max(>1.B; 5 m)	
Retaining structures	$H_w < 0$	h			max(0.4 x h ; F + 2 m)	
	$H_w > 0$	i			max(1.0 x H_w + 2 m ; F + 2 m)	
Anchors		j				
Reinforced fill structures		k	X m			
Ground reinforcing elements		l	X m			
Ground improvement		m				
		n				
Groundwater control			X m			
Underground structures		o			B	2 x B

Source: Authors' own work.

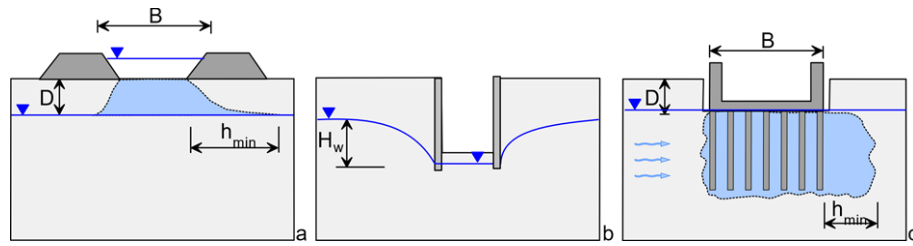
The positioning of in-situ testing locations should be based on the results of the expected load distribution of the structure or structures in the ZOI, see Figure 14 and Figure 15.

In the case of foundation structures, the depth of influence should at least, extend to the bottom of the deepest fine soil layer (or layer of high compressibility) that could undergo consolidation settlement. It should be noted that the zone of influence under cyclic, dynamic (vibration) or seismic actions can extend significantly beyond the zone of influence under static loading.

Vibration due to works such as sheet piling driving may also provide information regarding the extent of the ZOI. In the case where there is interaction of the planned works with surface water and groundwater table, the plume created during the lifetime of the structure may extend beyond the mechanical zone of influence (ZOI).

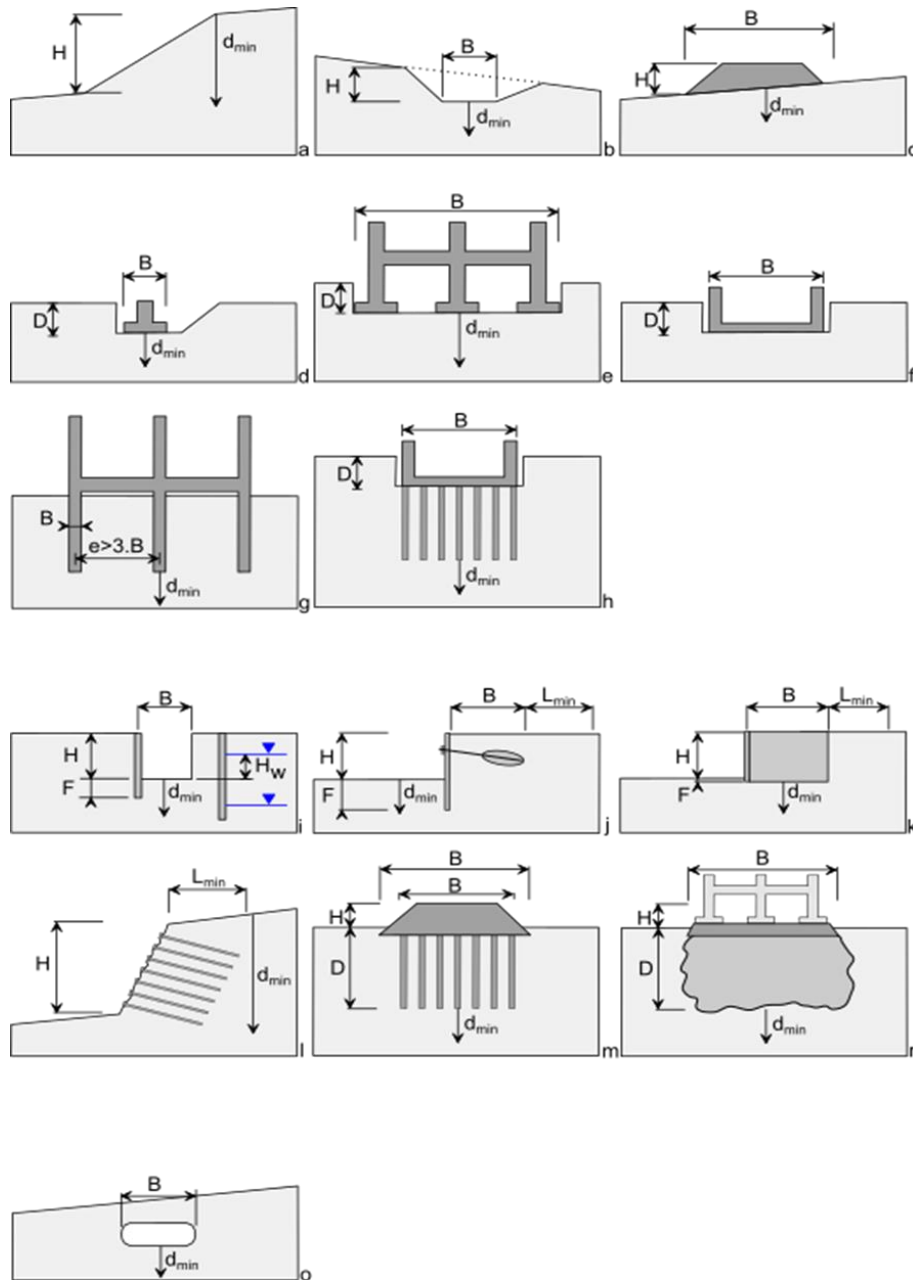
This definition of ZOI is also valid for geothermal structures such as pumping or thermo-active piles.

Figure 14. The extent of the zone of influence or investigation according to the structures.



Source: Authors' own work.

Figure 15. Spacing and depth of geotechnical zone of influence according to the structures.



Source: Authors' own work.

4 Derived values

4.1 General

According to EN 1997-1:2024 the derived value of a ground property can be assumed as a value of a ground property obtained by theory, correlation or empiricism, from field measurements or results of laboratory tests. Derived values of ground properties are to be established from data gathered during desk study, site inspection, preliminary and design investigations, as well as monitoring of the ground and structures.

The structure of this chapter follows the steps to define a ground model. Therefore, the geometrical inputs to the Ground Model are considered first. The derived values of different parameters are summarized according to their supposed relevance during Ground Model definition. In this context, it follows the structure of EN 1997-2:2024. The derived parameters should be determined for ground conditions representative of the site, i.e. for the correct strain- and stress-level and stress path. For the determination procedures for derived values for ground properties in the specific test standards and correlations, reference should be made to EN 1997-2:2024 and Annexes B, E, F, G. Derived values of ground properties are to be documented in the ground investigation report (GIR). The uncertainty of a derived value should be mentioned, and the quality of the data used. Chapter 5.3 contains basic information on uncertainties in the context of ground properties e.g. measured data and derived values. Detailed information on uncertainties of the geometrical model is given in chapter 5.4.

4.2 Geometrical properties

Derived values should be spatially assigned to a geometrical modelling of the site under consideration. The geometrical modelling forms a key part of the Ground Model. Geometrical characteristics representing the geometrical modelling should be defined in the geographic reference space to derive 2D- or 3D-representations, depending on the analysis to be performed.

According to EN 1997-1:2024 (4.3.3) for deriving geometrical properties the following information/elements should be considered:

- Surface data from geological charts/reliefs:
stratigraphic limits, layering orientation, tectonic discontinuities (faults and thrust faults).
- The geometry of the stratification: This information is derived from geological and geotechnical surveys. The stratigraphy obtained from different boreholes drilling and cone penetration tests (CPTs) could be interpolated, and the spatial result should be validated by deep investigation (geophysical surveys).
- Structural analyses:
The geometry of the discontinuities: information of location, orientation, spacing, extent, voids or openings, and surface roughness. Discontinuities may be grouped into sets that have similar dip and strike. Potential foliation should be identified.
- Estimation of shape and size of the representative rock volumes:
location and geometrical characteristics of rock volumes present in the area of interest could act as obstacles.
- Shape and size of any possible cavity inside the soil/rock mass.

- Digital Terrain Model:
The resolution of the model has to be appropriate to the analyses performed. The resolution depends on the scale to which the project refers, the detail required by the methods used for the analyses, and the type of analyses to be performed (numerical, analytical, empirical, etc.).
- Geometry and dimensions of existing structures in the area of interest (buildings, roads, bridges, etc.), with a level of detail appropriate to the scale of interest and the analyses performed.

4.3 Description and classification of the ground

According to EN 1997-2:2024 chapter 6 the derived values of ground parameters for description and classification of the ground considers natural exposures, artificial exposures created as part of the investigation and all samples recovered in the investigation are to be inspected and described.

Basically, for soil, the procedure should comply with EN ISO 14688:2017 (both parts).

In the same context for rock, the procedure should comply with EN ISO 14689:2017 and can consider the use of rock-mass classification systems.

4.4 State, physical and chemical properties

According to EN 1997-2:2024 chapter 7 the derived values of the following ground properties are to be considered, depending on the nature of the geotechnical problems to be analysed within the frames of a given project. State and physical properties comprise but are not limited to:

- water content, bulk density
- Porosity
- Saturation
- density index
- particle size distribution
- in-situ stress state
- particle density, Atterberg limits
- maximum and minimum void ratios
- particle shape
- soil dispersibility, erodibility
- compactibility

For rock masses, the derived values of the following state and physical properties should further be considered:

- shape and size of representative rock blocks;
- weathering and alteration of rock and discontinuities;
- roughness, opening and infilling of the discontinuities; Abrasiveness;
- rock degradation, (stability of rock in air or in water),

- sensitivity to dissolution and chemical weathering (rocks containing magnesium and calcium carbonate);
- in-situ stress state.

Chemical properties comprise but are not limited to:

- mineralogical and petrographic composition of the rock;
- organic matter content;
- carbonate content;
- sulphate and sulphide content;
- chloride and other salts content;
- pH;
- radioactivity – radon.

4.5 Strength

According to EN 1997-2:2024, chapter 8, the derived values of strength parameters comprise friction angle, and cohesion intercept. They are described either as total or effective stress parameters for both saturated and unsaturated soils.

For rock material, rock discontinuities and rock masses, the derived values of the strength parameters include:

- The angle of friction and apparent cohesion of rock masses (Mohr-Coulomb envelope);
- The angle of friction and apparent cohesion of discontinuities (Mohr-Coulomb envelope);
- Parameters of m , s and a of rock material and rock masses (Hoek-Brown envelope);
- Joint roughness coefficient (JRC), joint wall compressive strength (JCS) and residual angle of friction of rock discontinuities (Barton-Bandis envelope);
- Uniaxial compressive strength, tensile strength, and flexural strength of rock material.

4.6 Stiffness, compressibility and consolidation

According to EN 1997-2:2024, chapter 9, the derived values of stiffness, compressibility and consolidation properties comprise:

- relevant stiffness moduli representing expected stress and strain ranges;
- compression and recompression indexes;
- one-dimensional compressibility;
- coefficient of vertical consolidation;
- coefficient of horizontal consolidation;
- coefficient of secondary compression;

- pre-consolidation pressure;
- swelling properties.

When dealing with rock masses, the rock material elastic module and the tangential and normal stiffness of the discontinuities are relevant, representing expected stress and strain ranges. If the rock mass is modelled as an equivalent continuum, the rock mass stiffness must consider the effect of the discontinuity pattern and its stiffness. Rock mass classification systems may be used to estimate the rock mass stiffness when appropriate.

4.7 Cyclic, dynamic and seismic properties

According to EN 1997-2:2024, chapter 10, the derived values of cyclic, dynamic, and seismic properties comprise:

- cyclic response;
- variation of secant shear modulus and damping ratio against cyclic shear strain;
- very small strain moduli and wave velocities,
- excess pore water pressure,
- cyclic shear strength,
- depth to seismic bedrock,
- fundamental frequency of soil deposits.

4.8 Groundwater and geohydraulic properties

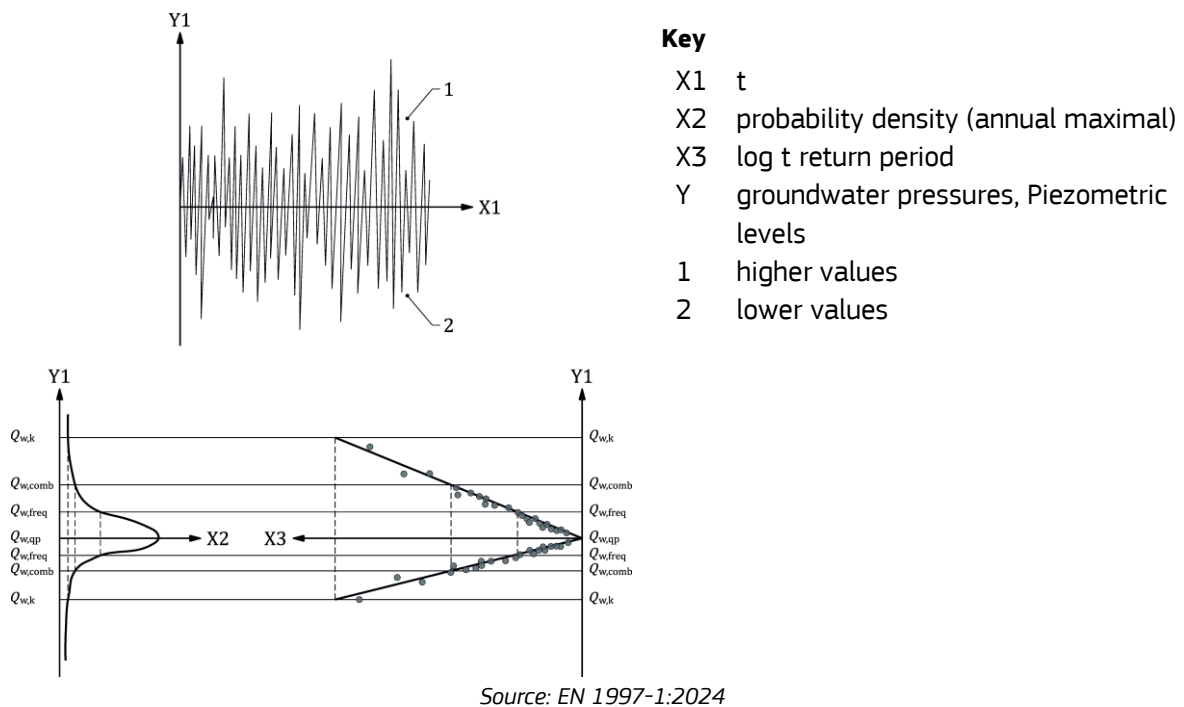
Groundwater is generally defined by the groundwater pressure/level and its fluctuations over time. Therefore, high and low groundwater levels should be indicated. Depending on the project requirements, different return periods can be set, and corresponding groundwater levels derived.

When assessing the relevant groundwater levels, the valid legal situation regarding groundwater protection and remaining flow capacities must be considered.

When specifying groundwater levels based on time series, the influence of existing pumping stations must be taken into account. If these pumping stations are abandoned, higher groundwater levels may occur than those recorded.

Figure 16 provides one example of a method of displaying groundwater pressures.

Figure 16. Representative values of groundwater pressures — illustration of characteristic, combination, frequent, and quasi-permanent values.



If water and/or seepage flow has/have a decisive influence, special geotechnical phenomena such as deformations of the subsoil (e.g. groundwater seepage into salt layers) and supporting structure, gap formation, permeability, water pressure, flow or pressure conditions, internal erosion must be considered.

Hydraulic conductivity (permeability), transmissivity and storage coefficient are determined mainly by pumping tests. Depending on the stratification of the subsoil, the horizontal values are recorded. In the case of excavations, on the other hand, the vertical permeability (e.g. from falling or constant head tests on undisturbed soil samples) is usually required and must be specified in the Ground Model. For rock masses, Lugeon-type water pressure tests, (see EN ISO 22282-3⁶), are usually performed. Water pressures in the zones containing discontinuities and weaknesses are significant parameters.

According to EN 1997-2:2024, chapter 11, the derived values of groundwater and geohydraulic properties comprise:

- groundwater pressure/head determination and its fluctuations over time;
- pore pressures,
- permeability (hydraulic conductivity).

⁶ EN ISO 22282-3:2012 *Geotechnical investigation and testing — Geohydraulic testing – Part 3: Water pressure tests in rock*, International Organization for Standardization ISO, 2012

In the rock mass on discontinuities (joints) and zones of weakness, the water intake capacity (water absorption) can be a significant parameter.

4.9 Geothermal properties

According to EN 1997-2:2024, chapter 12, the derived values of geothermal properties basically are:

- thermal conductivity of the ground,
- frost susceptibility,
- heat capacity;
- thermal diffusivity;
- thermal linear expansion.

Taking the special behaviour of rock into account, specifications like thermal linear expansion and frost susceptibility (for selected weathered rocks) are to be considered. Indeed, the main problem for the rock mass is the freezing of water in weathered rock leading to frost expansion and rock fall.

4.10 Geophysical information

The geophysical methods measure physical properties (electric resistivity, the velocity of different wave types, gravimetric and magnetic field intensity, etc.) to characterise ground properties which are different from those commonly used in geotechnical engineering practice (grain size distribution, consistency index, density index, elastic modulus, crack density, rock discontinuity pattern, etc.). Nevertheless, when correctly interpreted, the geophysical data can contain useful information to help inform the Ground Model, especially in areas where little or no information is available (in between and outside of the geotechnical investigation points).

The most commonly used information from geophysical data is the geometry of the boundaries between different soil/rock layers. This is relatively easy to assess but it always comes with a certain degree of uncertainty, depending on the depth of the boundary, the spatial resolution of the set-up, the sharpness of the geophysical contrast between layers, the complexity of the site's geology and the intrinsic uncertainty of the geophysical model. To minimise this uncertainty, the geophysical model must be 'calibrated' with direct information, at least one or two points along a profile, preferably towards the centre of the profile.

In the case of seismic methods, the measured wave velocities (especially Vs) can be directly linked to the ground mechanical properties of both soil and rock. For the other methods, the physical and/or mechanical properties can be roughly estimated and must be correlated with direct measurements. The success of this correlation depends on the interpreter's experience, the heterogeneity of the ground profile and the number of direct investigation points.

Geophysical investigations can provide valuable information regarding:

- archaeological sites for identifying possible buried structures, voids, and contamination;
- sites with complex geology where an accurate Ground Model cannot be obtained just from common ground investigations;

- sites where the boundary between sound rock and altered zone/overlying soil must be highlighted;
- sites for which no information is available, and the planning of the geotechnical investigation can be optimised by previous geophysical investigations;
- sites constituted by strongly heterogeneous materials;
- depth of groundwater table (electrical methods and GPR) and fresh-salt water interface (coastal areas) (Electrical methods);
- boundary between cohesive and non-cohesive sediments in soft sediments in fresh groundwater (electrical methods);
- ground properties for site response analysis;
- Susceptibility for liquefaction based on V_s (e.g. MASW⁷);
- Layering – structures in soft sediments above the groundwater table (GPR).

⁷ Multichannel Analysis of Surface Waves

5 Ground model uncertainties

5.1 General

The Ground Model should include the derived values of the relevant ground properties for all the geotechnical units encountered in the zone of influence. Several sources of uncertainties appear during the process of assembling the Ground Model and the derived values. Therefore, throughout the process, care must be taken to minimise these uncertainties.

The sources of uncertainties in assembling the detailed GM in the ZOI are related to:

- the accuracy of the information in already available ground investigations, including desk-study and site-inspection;
- the accuracy of available geological description, hydrological and geological information, and geological 3D models,
- the accuracy of existing 3D models used as a basis in new 3D models,
- the position- and depth measurement of the new ground investigation;
- interpretation of the results from new ground investigations:
 - CPT, FVT, SPT, PMT⁸, etc.
 - Borehole-data: determination of geological formation with intrinsic dependency on the experience of the interpreter (geologist)
 - Water: Piezometer, etc.
- the unknown shape of the boundary between measurements (2 points): straight lines, curved lines;
- the presence of manmade hard inclusions (historical foundations, cables, sewerage pipes, ...).

Other hidden uncertainties may exist such as the one that originates from a too-large adaptation of the investigation program to the shape of the ZOI. The spatial heterogeneity of the investigations may then be a problem, especially in the case of linear infrastructures, which leads to longitudinal over-information.

The definition and treatment of uncertainties encountered during ground investigation testing for derived values are detailed in the test standards.

The use of geostatistical tools to analyse a set of derived values for a reliability-based design and derivation of partial factors are described in the Guideline document 'Reliability-based methods for geotechnical design and assessment' drafted by TC250/SC7/TG-C3.

This chapter further elaborates on the following sources of uncertainty in the Ground Model; those related to the derivation of ground properties, those related to assembling the units/layers and those related to handling a large amount of data.

⁸ Cone Penetration Test, Field Vane Test, Standard Penetration Test, Pressuremeter Test

5.2 Uncertainty in derived values of ground properties

5.2.1 General

The definition and treatment of uncertainties in the process to determine representative values based on derived values are described in the Guideline document 'Derived to design value' drafted by TC250/SC7/TG-C1. The main concepts of reliability are covered in the Guideline document 'Reliability-based methods for geotechnical design and assessment' drafted by TC250/SC7/TG-C3 but some specific concepts of geostatistics applied to ground investigation are recalled below for clarity and to make this document independently understandable.

Uncertainties in the assembled ground model are partly originated from uncertainties encountered in the process of ground properties definition and parameter values derivation.

Generally, there are three types of uncertainties and errors:

- those of observation;
- those of investigation;
- the natural variability of properties from one point to another in space which, if not perfectly known, is modelled as an error.

5.2.2 Observation uncertainties: during the measurement

The errors of observation include themselves:

- the measurement error due to the apparatus and the operator;
- the error of representativeness, the parameter not being directly measured but expressed by a ratio, a difference, etc., and even sometimes by a correlation;
- the error of the moment due to the instability or the modification of the observed quantity over time. This is the case of reworking, which generally leads to an underestimation of the magnitude, or of damage, creep and fatigue, which leads to an overestimation.

The estimation of the accuracy (trueness and precision) of the test method is done with the help of the standard ISO 5725-1 to 6 - Accuracy (trueness and precision) of measurement results and methods. The implementation of uncertainty calculations is done within the framework of a quality system of the standard: EN ISO/IEC 17025: 2017⁹ - General requirements for the competence of testing and calibration laboratories. Most of the test standards giving access to parameters listed by

EN 1997-2:2024 suggest performing an uncertainty calculation on the result obtained using these methods.

However, no guidance is provided for the analyses of a set of soundings. Engineers must refer to EN 1990:2023, Annex D (D.5 to D.7).

⁹ EN ISO/IEC 17025: 2017 *General requirements for the competence of testing and calibration laboratories*, International Organization for Standardization, 2017

5.2.3 Uncertainties of investigations: during the gathering of data

As for the investigation uncertainties, they include:

- on one hand, systematic/epistemic errors due to an inappropriate organisation of investigation: so for example weak zones could be missed and this could compromise structural integrity. We call them investigation uncertainties. To reduce these uncertainties, EN 1997-2:2024 proposes in Annex H a minimum investigation density, and EN 1997-3 provides advice on adapting the investigation to the type of structure.
- on the other hand, the random sampling or random error, which is not related to the observed quantity, but to the estimation of a characteristic of its distribution (estimation of the expected value (i.e. mean), the variance, the autocorrelation). It is not an error, in the previously defined sense, but an estimation error, a random variable characterising the difference between an unknown but certain quantity existing in the population and the estimate that can be made from the values observed on the sample. It depends strongly on the size of the sample, i.e. the number of measurements.

5.2.4 Due to spatial variability

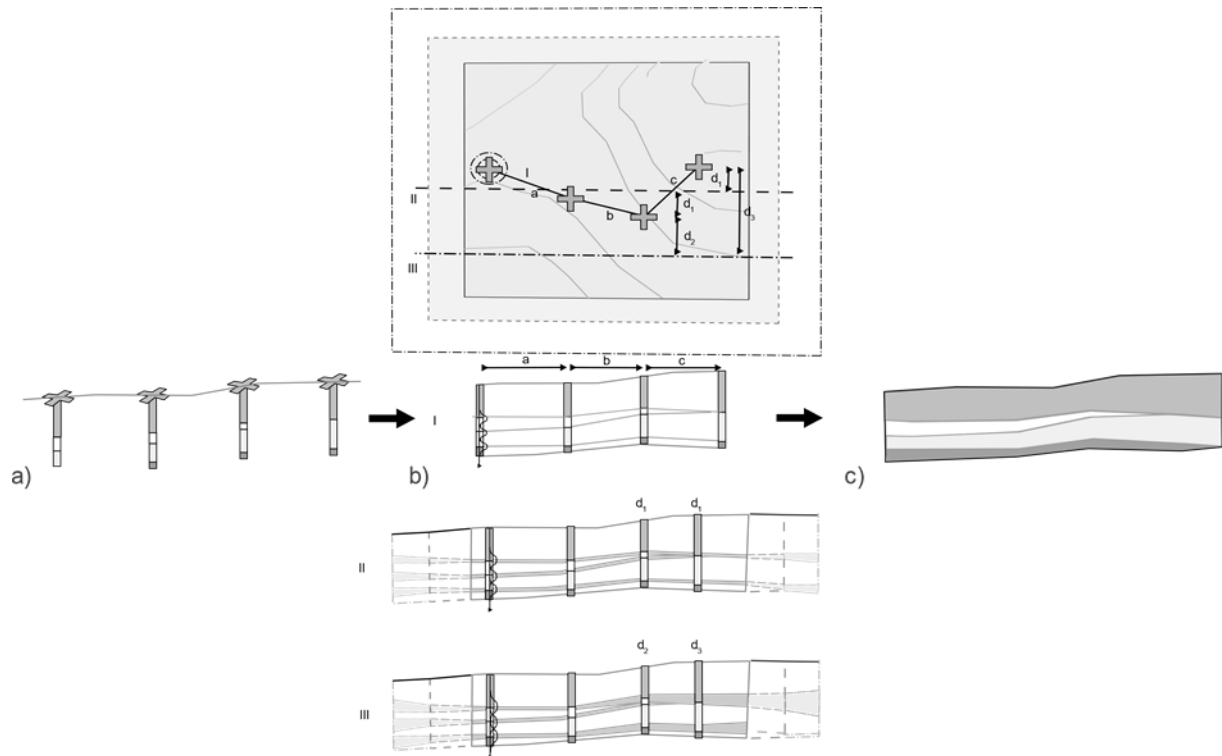
The origin of natural ground, (both soil and rock) more than any other material, is the result of a complex depositional (and sometimes subsequent structural) process in which multiple mechanical and chemical factors have been involved. Its characteristics present true values that differ from one point to another in space, and it is impossible to take them into account in detail for the calculation of structures. Therefore, this natural variability is modelled as an error, i.e. as a variance around an average trend that can be a function of space. This 'point' variance, that of the natural value at each point, must be completed by the autocorrelation function which measures the dependence of nearby values, and which plays, by integration, an essential role as a reducer of the variance of the calculation results. The distance from which the dependence is zero or almost zero is called the fluctuation range or the autocorrelation distance.

5.3 Uncertainty in assembling the model geometry.

The transition from the representation of drilling type information that can be described as one-dimensional (we only know the information in one direction of space) to a two-dimensional representation with cross-sections or three-dimensional representation requires the use of a certain number of tools. Usually, this integration is done manually and largely based on engineering judgement and experience and resulting in additional uncertainties.

To define the uncertainties associated with ZOI, the designer should plan for the correct amount of investigation. Interpolation should be used with caution and mainly for graphical purposes. Extrapolation of the Ground Model introduces even more uncertainties in the final geometry. Similarly, the projection of investigation results on to a plane passing between or outside the fence defined by the sounding locations leads to increased uncertainties in the vertical positioning of the layer interfaces. Figure 17 schematically illustrates this process. The following paragraphs describe in more detail some of the aspects that may require attention.

Figure 17. Building cross-sections – correlation of geological units from the surface geological map and borehole logs.



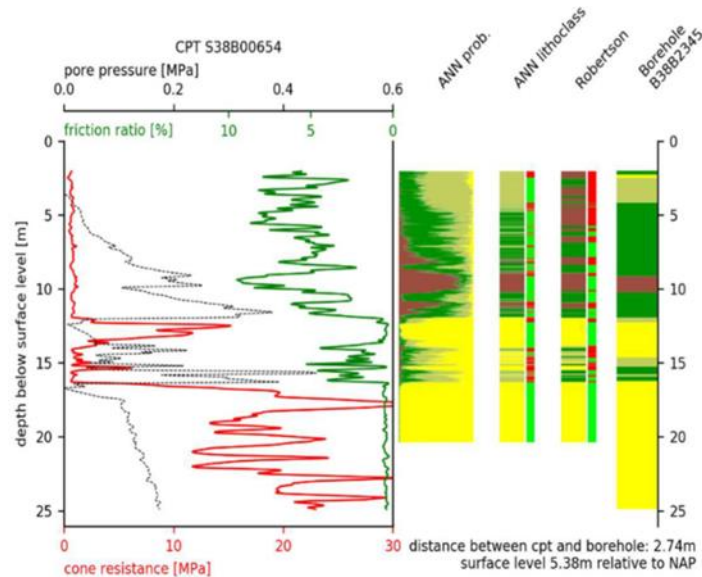
Source: Authors' own work.

The identification of the lithology that can be matched between the different boreholes according to the identification of the ground layers and the mechanical parameters depends on the distance between the boreholes, the difference in level between the layers compared, and a similarity index. A good correspondence suggests a stratigraphic link between the layers.

Various techniques may be used to form a decision tree (chart, tables, etc.), or the 'Random Forest' technique with artificial neural network (ANN), depending on the regional practice, projects, expertise, national rules, etc. Note that soil classification is country dependent. For example, in Belgium, the layering of CPTs is based on Table 2.1 of EN 1997-1:2024.

Figure 18 shows an example of soil classification performed using the Robertson chart and machine learning.

Figure 18. Comparison of soil classification using Robertson chart and ANN techniques.



Source: Kars et al. (2021)

Once the description, classification or mechanical characterisation is achieved at a particular 1D location (i.e. borehole), the graphical representation needs to fill the gap by interpolation techniques:

- IDW: Inverse distance weighting;
- minimum curvature method;
- irregular triangulation with smoothing;
- Triangulated irregular network based (TIN-based);
- rectangular interpolation;
- local polynomial,
- kriging.

In practice, these Individual 1D stratigraphies may be jointly interpreted with diverse geophysical surveys to derive a single model of the investigated subsurface region. This approach is, however, largely qualitative, and hence the outcome depends heavily on the background, experience and preconceptions of the interpreter.

Interpolation is also a need for:

- Determination of the zones of higher risk,
- Determination of areas where more ground investigation is needed;
- Volume calculation of excavation.

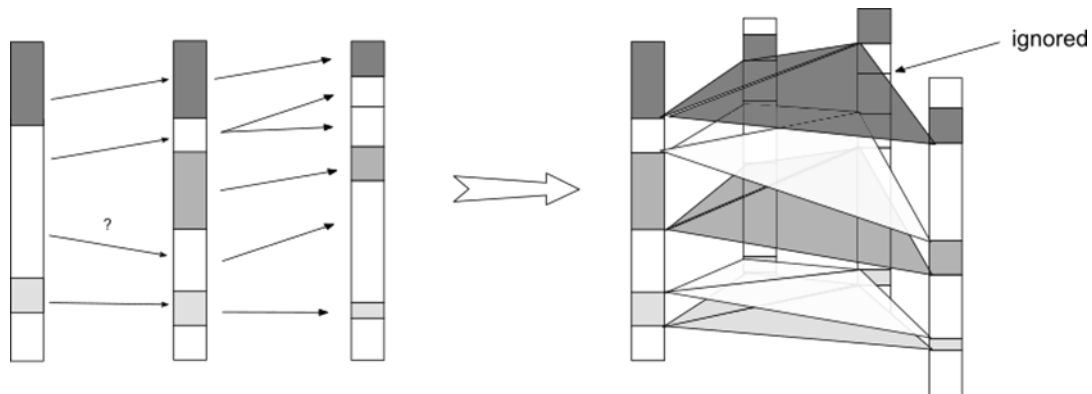
However, in most practice, interpolation should not be used for determining the layering used in the geotechnical design calculation. In the Ground Model, a clear distinction should be made between the locations where the ground layering was measured and the areas between measurements.

Figure 19 shows how the Ground Model develops and improves during the iterative process of the project.

When one of the boreholes is much deeper, a lower boundary is defined to limit the area of comparison. Considering a particular structural context (network faults) can also lead to limiting the area of comparison.

The construction of links and remarkable planes is thus done for boreholes that are approximately in the same plane.

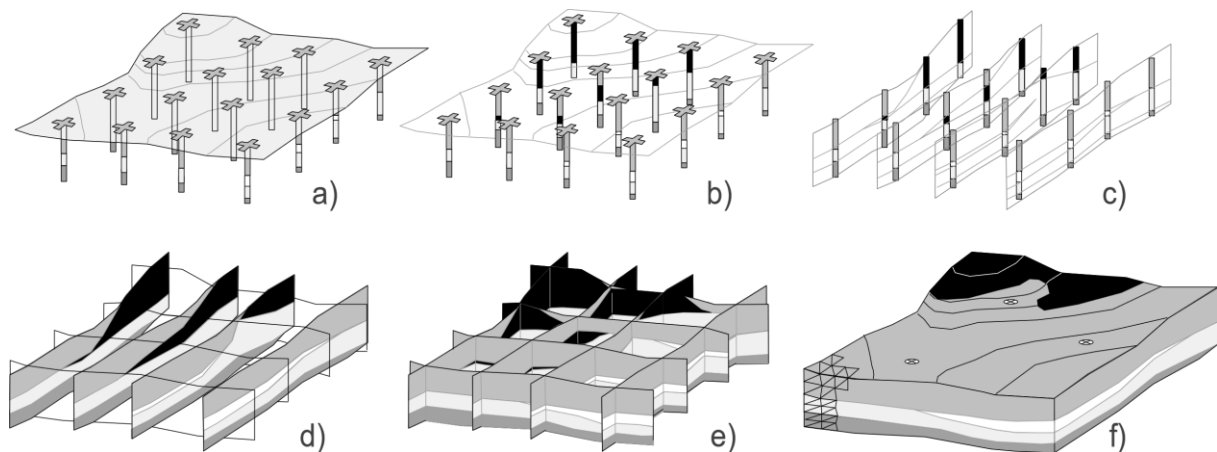
Figure 19. Procedure for interpreting boreholes and recreating lithology.



Source: Authors' own work.

The procedure is continued for an approximately orthogonal direction using the same approach, as shown in Figure 20. Once the 3D connection (or 'fence') is completed, interpolation methods are used to fill in the unsampled areas to establish a Digital Terrain Model volumetric model.

Figure 20. Schematic example of a fence diagram used to develop the 3D model.



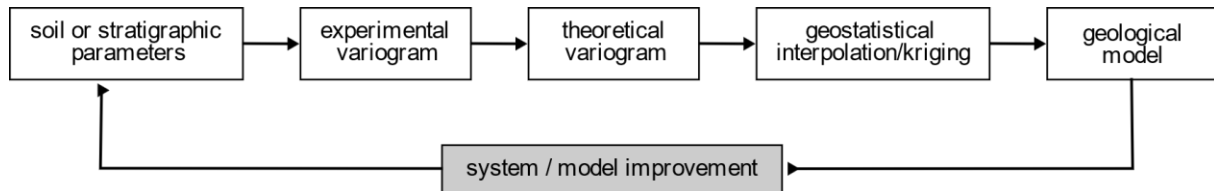
Source: Authors' own work.

5.4 Computerised interpretation – uncertainty in a large amount of data

The statistical study applied to geotechnical properties derived from field testing has the objective of determining characteristics defining a homogeneous zone for computerised interpretation of profiles. The applied techniques are either based on simple variables (mean, median, standard

deviation, asymmetry, flattening, etc.) or developed for specific variables: index of homogeneity or on the variogram or the autocorrelation analysis. It has to be considered that ground properties are test dependent and may vary depending on various control variables, which are not always measured (stress path, speed of rotation, etc.), comp. Figure 21 and Figure 22.

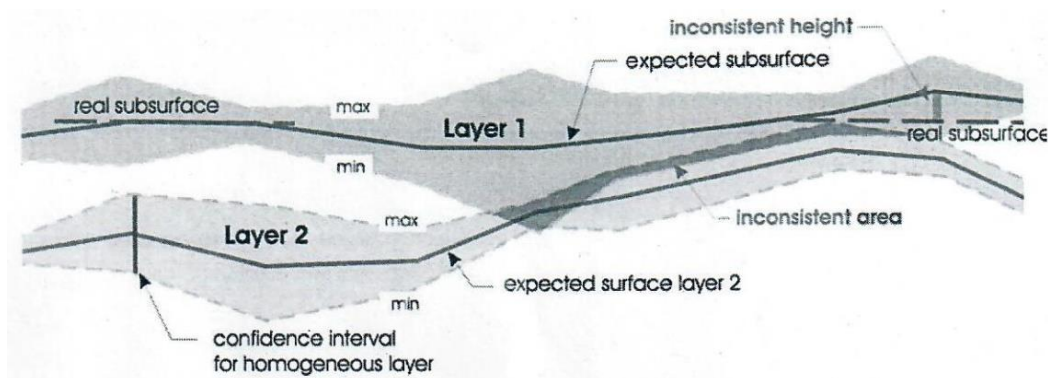
Figure 21. Structure of geostatistical modelling.



Source: Schönhardt, Wudtke and Witt (2007)

The model needs to be constructed from pertinent initial values and needs a minimum of data to converge to a pertinent proposition of the ground model. These techniques require significant local experience to assess their relevance in the application.

Figure 22. Construction of layers using a geostatistical process, inconsistent sections inside impoundment models due to uncertainties value.



Source: Schönhardt, Wudtke and Witt (2007)

5.5 Ground model validation

The validation of the Ground Model may be done by applying complementary rules or laws:

— principles of geology:

- principle of continuity (same age throughout);
- principle of superposition (in most cases, recent ground has the oldest layers underneath, but rocks may have layers inverted by folding), (1);
- principle of uniformity and stationarity (same causes give same effects).

Note (1): it should be noted that there are stratigraphic units that have been overturned due to the effects of folding. Also, in areas of landslip, older materials may be present apparently overlying younger materials.

— existing site model, or detailed knowledge of the ground and groundwater:

- highly deformable surface layer resting on increasingly resistant layers up to the substratum;
 - irregular stacking of alluvial terraces in a river valley;
 - plain with regular horizontal stratigraphy cut by a fossil canyon filled with other materials;
 - the transition zone between different materials or facies of materials;
 - homogeneous massif with lenses of other materials, etc.;
- the interfaces of layers of different types of terrain were free surfaces before the deposition of the overlying layer: they follow the general rules of terrestrial or marine geomorphology, depending on the case;
- any geological structure corresponds to a formation mechanism, a combination of alteration, sedimentation, erosion, tectonic movements, etc.

5.6 How to represent uncertainties

The traditional visualisation approach of uncertainties is at the least to show a range or confidence interval. A point in the middle represents a mean or median, and a bar or line shows other possible values or coverage. However, as described in 4.3, it is not suitable for the stratigraphic type of representation. Other solutions exist: 'Multiple Outcomes' that may be faded accounting of their probability, 'Obscurity or Colours' (like what colour, what texture, how much saturation and hue etc.), etc.

Moreover, consideration has to be given to how to represent:

- data completeness: the extent to which information is comprehensive;
- consistency: the extent to which information components agree;
- temporal uncertainty: are data collected in the same time frame and still valid?
- spatial uncertainty: scale adapted to precision levels in ZOI.

It is important to remember that the final purpose is to improve transparency on the quality of data underlying a map without compromising the ease of theme interpretation.

There are various options to represent uncertainties:

- graphically by colours or symbols, or surface/curves;
- explicit verbal notes on uncertainty boxed along on a map attached to an object or with the map legend.

Further reading is suggested:

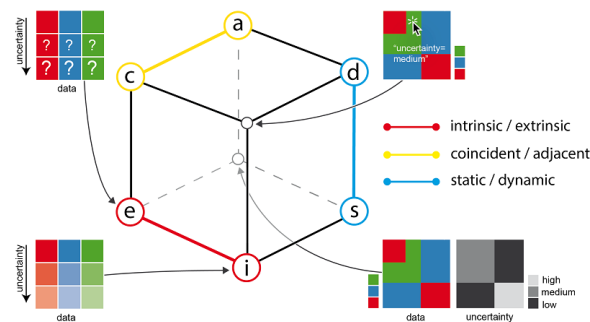
- <https://proceedings.esri.com/library/userconf/proc05/papers/pap1153.pdf>.
- <https://gistbok.ucgis.org/bok-topics/representing-uncertainty>.

A wide range of approaches for a visual representation of uncertainty exists, and it can be challenging to select techniques suitable for specific applications and user tasks. One way to provide guidance with this procedure is to use typologies that help categorise approaches and techniques. Similar to the typologies used to organise different types of uncertainty, there are typologies for uncertainty visualisation that suggest techniques for certain types of data

(areas/points/lines, discrete/continuous etc.) and types of uncertainty (e.g. Battenfield & Weibel, 1988; Pang et al., 1997; Sanyal et al., 2009).

Kinkeldey et al. (2014) outline a framework called UVis3 (uncertainty visualisation cube) that describes all uncertainty representation approaches based on three design axes: (1) intrinsic/extrinsic, (2) coincident/adjacent, and (3) static / dynamic as shown in Figure 23. Each corner of the cube represents a combination of the three categories.

Figure 23. UVis3 (uncertainty visualisation cube), extended from Kinkeldey et al. (2014), including four examples: representation of uncertainty by symbol size (top left), colour value (bottom left), greyscale in a side-by-side view (bottom right), and by an invisible layer providing uncertainty retrieval through user interaction (top right).

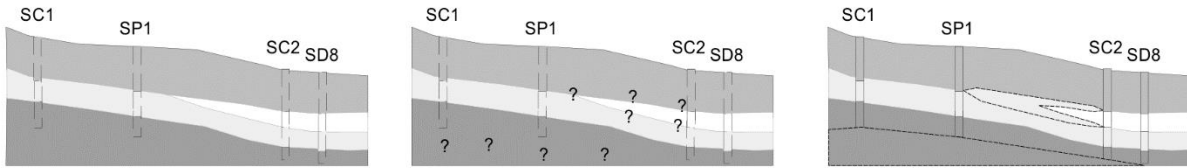


Source: Kinkeldey et al. (2014)

In this model:

- intrinsic/extrinsic describes whether uncertainty is represented as an attribute of existing visual objects (intrinsic, e.g. by manipulating their colour) or in the form of additional objects (extrinsic, e.g. symbols expressing the uncertainty). Common intrinsic techniques are colour value/lightness/brightness (lighter colour = higher level of uncertainty), transparency (more transparent = higher level of uncertainty) or saturation (less saturated = higher level of uncertainty). Apart from colour, the use of fuzziness (blur) to represent uncertain areas (blurry fill pattern) or boundaries (blurry line) falls into the 'intrinsic' category, as does texture (dashed or 'sketchy' lines, hatched areas or similar). Extrinsic techniques include overlaid symbols (crosshairs, emoticons), glyphs (crosses, circles), or isolines. Figure 23 shows an example of an intrinsic technique in the bottom left (colour value represents uncertainty) and an extrinsic technique in the top left (size of question marks represents uncertainty);
- coincident/adjacent describes whether the information about uncertainty is mapped to the same view as the data (coincident) or an additional view (adjacent). A coincident view example is bivariate maps that show the relationship between data and uncertainty. Adjacent views are, for instance, side-by-side views or small multiples. The bottom right example in Figure 23 is a simplified adjacent view where the data view on the left remains unchanged, and the related uncertainty is represented in the right view using a grey scale;
- static/dynamic describes whether animations and/or interactive means are used to represent uncertainty. The most common are static visualisations, but many approaches use animation (e.g. showing an uncertainty layer alternating with a data layer in Figure 24) or interaction (e.g. uncertainty can be retrieved by clicking on an area in a map, see the top right example in Figure 23).

Figure 24. Different representations of uncertain interface and zone.

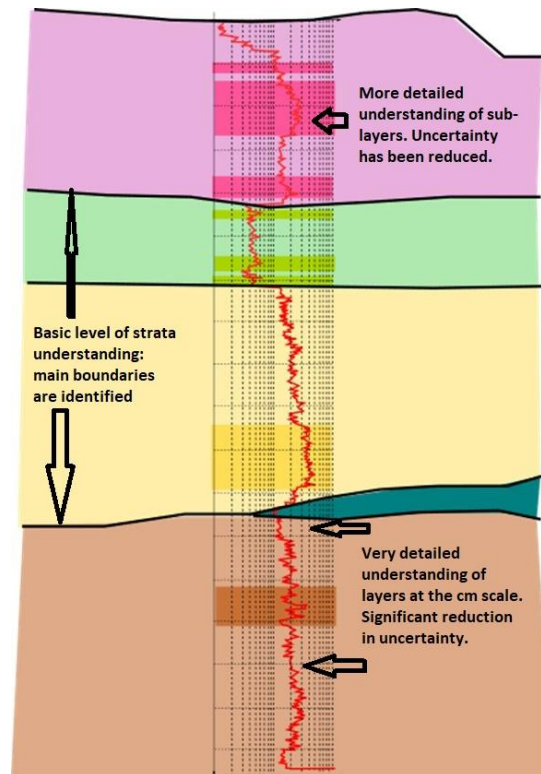


Source: Authors' own work.

Figure 25 shows three applications of these representations for the GM. Depending on the size and complexity of the Ground Model and the structure i.e. ranging from simple to complex, it demonstrates the following aspects that may be derived from a CPT:

- general layering SBT;
- more details layering (sublayers within the main SBT units);
- most detailed information per cm CPT data.

Figure 25. Example of reducing uncertainties from CPT data.



Source: Authors' own work.

6 Conclusions

The second generation of EN 1997-2:2024 introduces the philosophy of the Ground Model as a tool to present ground conditions during a project.

This guideline assists users in fulfilling their requirements and recommendations.

The second generation of EN 1997 places a clear requirement on the designer to consider the Ground Model in the design process.

For this purpose, EN 1997-2:2024 sets general rules to be followed. However, it is recognised that more specific guidance and examples are useful to foster the implementation of those rules in national practices and to better understand the intent behind the requirements and recommendations presented in the code.

This document aims to give guidance to the designer on how to meet the requirements placed on them in the design codes.

Declaration of AI assisted technologies in the writing process:

During the preparation of this work the author(s) used, OpenAI's GPT-3.5-turbo version, November 2023 (Model code: gpt-3.5-turbo-1106 / Service: GPT@JRC) to proofread the text in various sections of the document. After using this tool, the author(s) thoroughly reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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List of abbreviations and definitions

Abbreviations	Definitions
ANN	Artificial Neural Network
CCD	Charge-Coupled Device
CI	Continuity Index
CPT	Cone Penetration Test
FVT	Field Vane Test
GDM	Geotechnical design model
GDR	Geotechnical Design Report
GIR	Ground Investigation Report
GM	Ground Model
GPR	Ground-Penetrating Radar
IDW	Inverse Distance Weighting
JCS	Joint wall compressive strength
JRC	Joint roughness coefficient
LiDAR	Light Imaging Detection And Ranging
MASW	Multichannel Analysis of Surface Waves
NAP	Normal Amsterdams Peil or Amsterdam Ordnance Datum
PMT	Pressuremeter test
SPT	Standard Penetration Test
TIN	Triangulated Irregular Network
ZOI	Zone Of Influence

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Annexes

Annex 1. Examples – GC1 & GC2

Introduction

To illustrate how to meet the requirements for Ground Models (see definition below) evolving during subsequent project phases in the Eurocode, two case studies are presented for projects in the Netherlands.

Ground Model of the zone of influence for a project is defined in the Eurocode as a 'site-specific outline of the disposition and character of the ground and groundwater based on results from ground investigations and other available data'.

Geology

In most of the country, the top 50 m of the sub-soil consists of Holocene tidal and fluvatile deposits of clay, silt and peat followed by Pleistocene glacial, fluvatile mainly sandy sediments (all part of Upper North Sea Group). The phreatic groundwater table is usually within 1 m below surface and in the polder areas (26% of the country) the groundwater table in the sandy Pleistocene deposits can be more than 1 m above surface level. Most buildings have pile foundations. The main geotechnical risks are associated with settlement, and macro stability.

Available data

For a desk study a national database is available with: CPT data, borehole records, geotechnical laboratory analyses and time series of groundwater levels. For these data, standard XML data formats have been defined. Further a digital geological model of the top 35 m is available for a large part of the country (Voxels 100x100 m layer thickness 0,5 m), as well as a country-wide model providing hydrogeological characteristics of different lithostratigraphic layers (depth to 150 m), digital maps with historic land use, soil classification (top 1,2 m) and geomorphology. Information about subsurface infrastructure (e.g. cables-pipelines-sewage) can be accessed through a central digital facility. A national digital terrain model (grid size 5x5 m) is also available.

Case 1: construction of a house (GC1)

Introduction

The example for a GC1-category project concerns the construction of a house in Blauwestad, which is a new town and this house will be realised on former farmland. The house is free-standing and at the time of writing, no buildings or vulnerable infrastructures are present in the immediate surroundings. Hence, this is considered a CC1 structure. The house will get a pile foundation and will be without a basement.

Zone of influence (ZOI)

As the house will be realised on pile foundations and no excavation is required, for now, the ZOI will be limited to the property boundaries.

Desk study

Available sub-surface data

Table 8 summarises the historical data available for the surroundings of the site. Overall, a reasonable amount of research has already been done in the area. However, the available boreholes are fairly shallow (max. 3 metres below ground level) and have mainly only sampled the anthropogenic top layer and do not provide much insight into the area's 'original' lithostratigraphy. A geological voxel model for the area (100x100x0.5 m scale) is available. Regarding the available borehole logs available in the national database, it should be noted that some of the boreholes are rather old (1930), whereas most of the remaining boreholes have no date available. It is likely the latter boreholes were also made before the creation of Blauwestad (and the heightening of the site).

Table 8. Summary of available historical data, by source; the attained depth is in m below ground level.

Data source	Data type	Number of points	Attained depth	Date of execution
W&P (Geoloket)	CPT	11	<25 m	2009-2021
	Manual borehole	4	<3 m	2021-2022
Dinoloket	Borehole	7	<6 m	1930,1996, unknown

Source: Authors' own work.

Lithostratigraphy

The lithostratigraphic build-up of the area is summarised in Table 9.

Table 9. Summary of the area's lithostratigraphy, based on the data presented in 2.3.1.

Formation	Member / bed	Depositional environment	Lithology	Depth interval (m NAP)	
				From ca.	To ca.
Naaldwijk	Walcheren m.	Estuarine	Clay, fine sand	Ground level	-2
Nieuwkoop	Basisveen b.	Marsh	Peat	Ground level	-3
Boxtel	Undiff. / Wierden m.	Periglacial; fluvial, aeolian	Sand, locally clay and peat	Ground level	-5
Drente	Undiff. / Gieten m.	Glacial; ground morene, fluvial	Sand, boulder clay (keileem)	-2	-5
Peelo	Undiff. / Nieuwolda m.	Glacial; lacustrine, fluvial	Overconsolidated clay (potklei)	-3	-6

Note that some parts of the area were heightened. The depth interval shows the approximate minimum and maximum depths between which a unit is expected to occur.

Undiff. = undifferentiated.

Source: Authors' own work.

Overall, the data indicate that the top few metres (down to max 6 m – NAP; (NAP is Normal Amsterdams Peil or Amsterdam Ordnance Datum)), are characterised by a rather heterogenic build-up, based on the available borehole data. These layers are hard to tell apart in the CPTs, as this part is generally quite thinly layered (resulting in convoluted CPT results) or consists of sand.

Below this heterogenic layer, only the Peelo formation¹⁰, see Table 9, is to be expected. The available CPTs in the national database (which are more representative for the site based on date of execution and proximity) indicate that the Peelo formation contains a lot more sand than is modelled in the geological voxel model. Furthermore, the location and thickness of these sand layers appear to show large lateral variations at very small distances.

Recent history

From the Middle Ages till the 20th century, peat extraction occurred through much of the Netherlands. At Blauwestad, the peat extraction resulted in a relatively deep polder; ground level at the site was approximately 1.3 m –NAP in 2004. In 2005, after dykes had been build, the area was flooded in order to create a lake, the 'Oldambtmeer'. In 'Het Riet', the part of Blauwestad the site is located in, artificial islands were created at the same time.

Topography

The site is at approximately 0.50 m + NAP. For example, the site has been heightened by approximately 2 metres. The available recent boreholes indicate that mostly silty sand, clayey sand and humus was used. Most likely, the material was locally sourced.

Desk study – summary

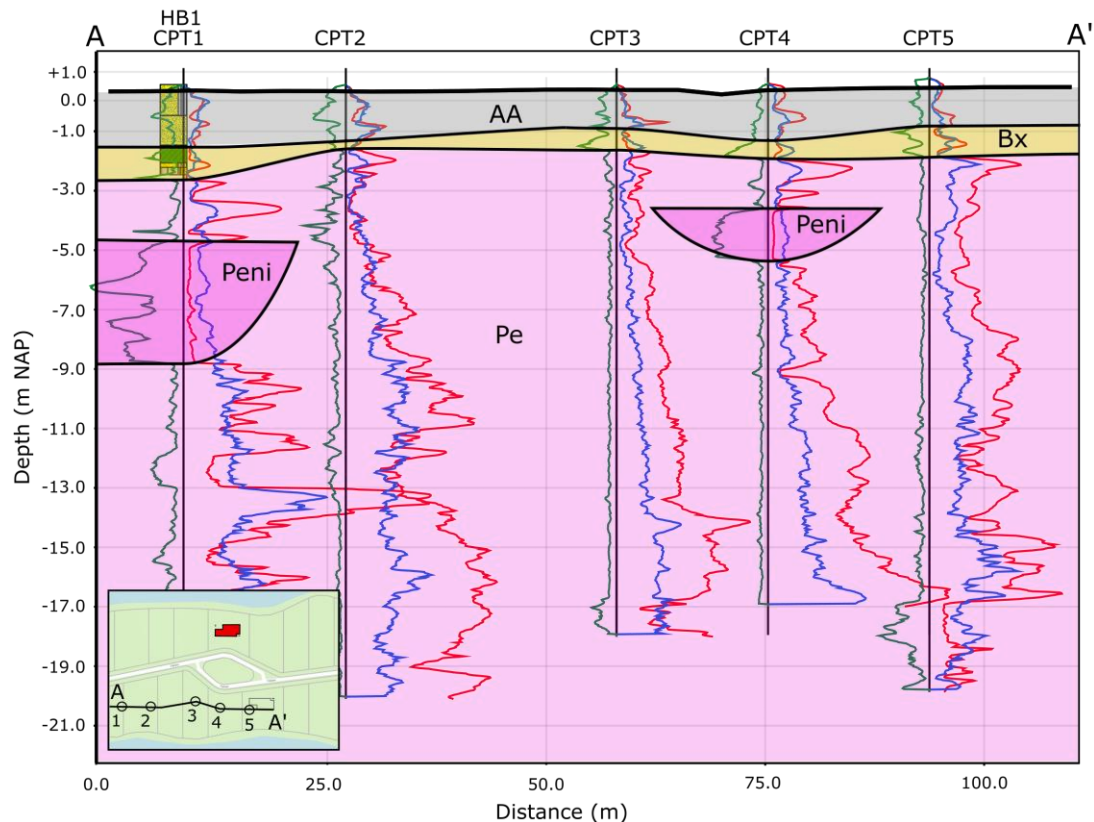
The cross section in Figure 26 summarises the lithostratigraphic composition of the surroundings of the site. In summary, the presently available data suggest that the site was heightened by two metres, using locally sourced material. Below this, a thin Holocene layer (sand, clay, locally peat, max. ca. 1 m thick) may locally be present. From here to 6 m – NAP, various Pleistocene formations may be present, which primarily are composed of sand, but may locally contain compressible layers (Boxtel clay or peat). From 6 m to 50 m – NAP, the Peelo formation is to be expected, although the exact top of the Peelo formation is hard to define in the available CPTs. The lithological build-up of the Peelo formation is highly laterally variable and consists of sand and over consolidated clay.

For a pile foundation, both the sand and the over consolidated clay of the Peelo formation would probably provide sufficient bearing capacity. However, the high lateral variability may result in pile tips lying both in clay and in sand, resulting in variable settlement behaviour. Furthermore, the exact start of the positive adhesion trajectory might be hard to determine, as the Basisveen bed (Holocene peat layer directly on top of the Pleistocene deposits) can be mistaken for over consolidated clay in the CPTs. Lastly, the ground conditions at the site would potentially allow for a shallow foundation, although it might require the removal of compressible layers up till the Basisveen bed (if present).

¹⁰ The so-called Peelo Formation (glaciolacustrine and turbiditic deposits) includes all of the Elsterian glacial deposits, ranging from silt and clay to coarse sand with fine gravel.

Based on the desk study, the chosen lateral ZOI appears to be appropriate. Based on the available CPT's the vertical ZOI is set at 25 m depth.

Figure 26. Cross-section made with historical data in the vicinity of the site (red square in map).



Source: Authors' own work.

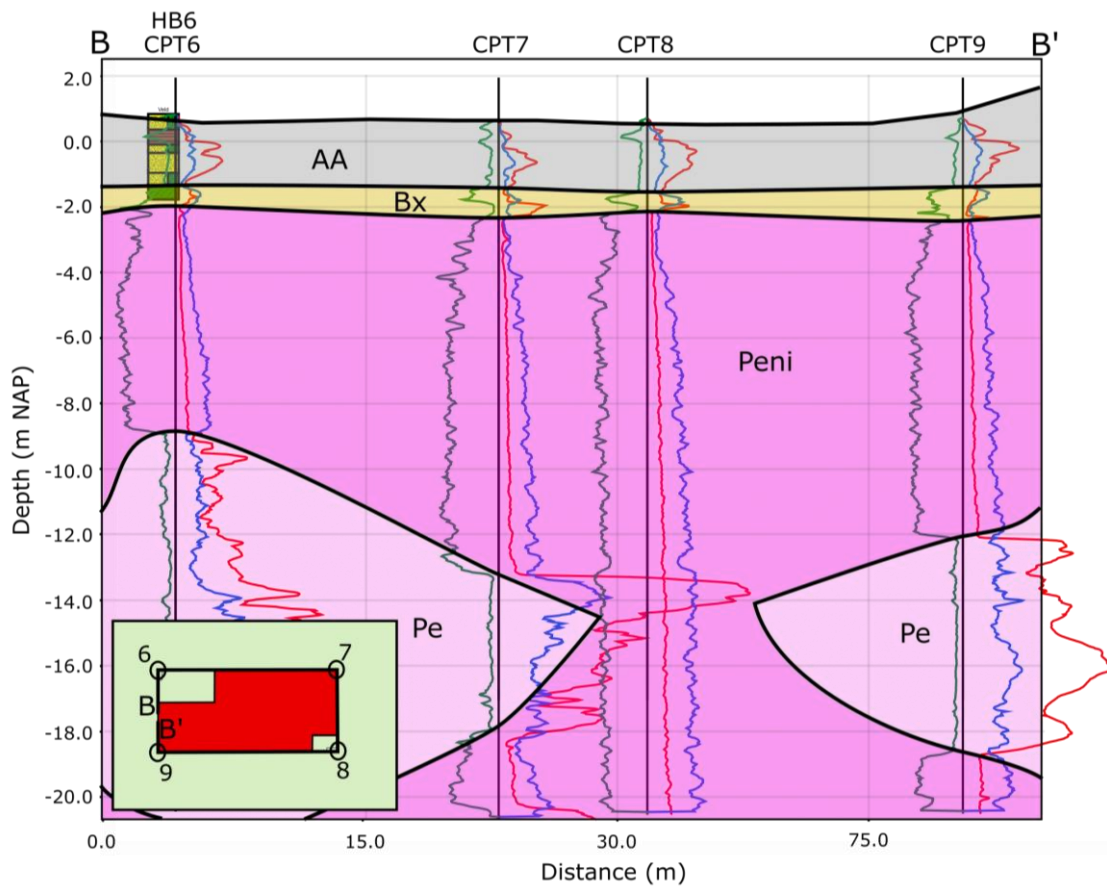
Investigation plan

Considering the house will have a pile foundation, it was suggested to perform a ground investigation consisting of four CPTs to 20 m below the surface at every corner of the house. However, if the lithological build-up of the Peelo formation below the site turns out to be too heterogeneous, additional CPTs may be required. Instead of the manual borehole, that's usually made for houses, it was suggested to take undisturbed samples using a track truck (CTP unit) down to 5 m below the surface, to have a better idea of the composition of the top layers. These samples should be taken near one of the CPTs, particularly the one with the highest friction numbers in the top few metres.

Fieldwork results

The results of the ground investigation are summarised in Figure 27. The undisturbed samples were taken near CPT017. The results are in line with the predictions from the desk study: over-consolidated clay belonging to the Peelo formation from at least 3 m – NAP, followed by a sand layer which is highly variable in vertical direction. At CPT020, the sand layer is completely absent. The top few metres primarily consist of sand, locally followed by a humus layer. The undisturbed samples indicate that at this site, the layers with high friction numbers within the first 5 m most likely do not consist of over-consolidated clay.

Figure 27. Cross-section based on the data collected for this project.



Source: Authors' own work.

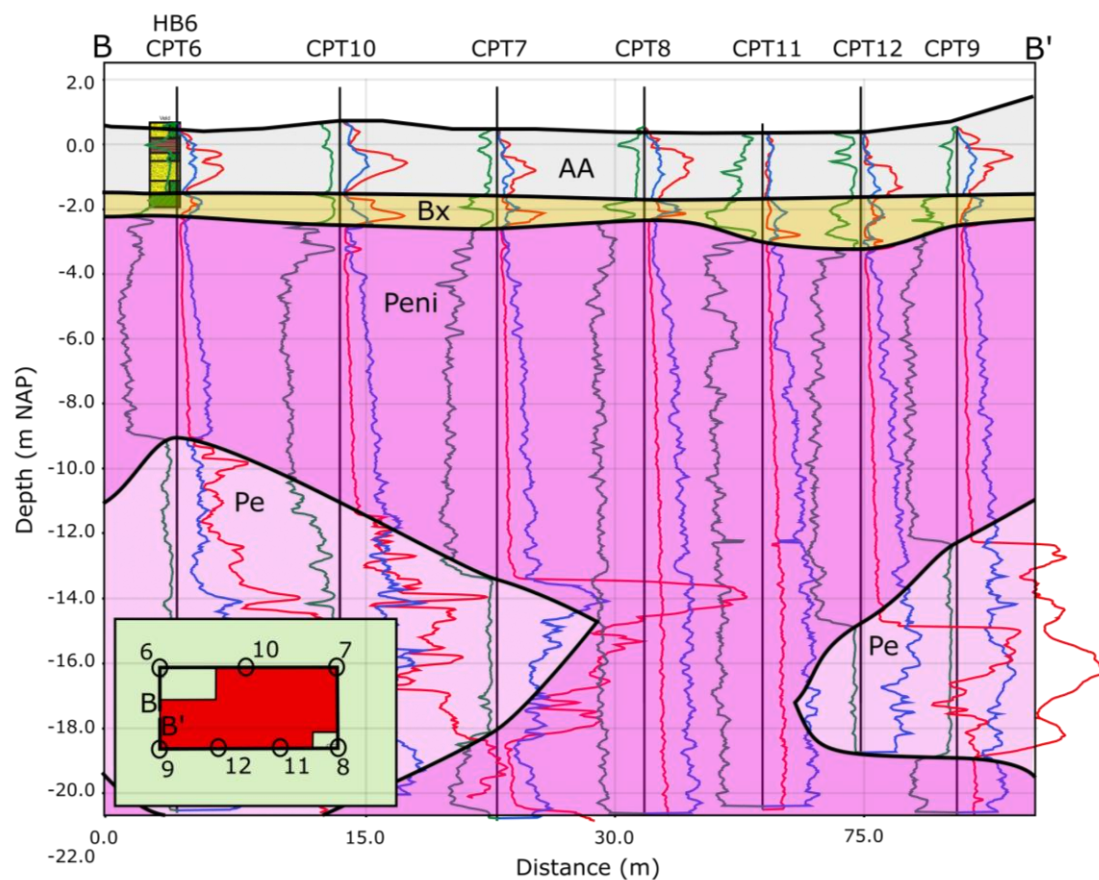
If one were to make a bearing capacity calculation based on the present data set, one would have to apply the results of the worst CPT (CPT020) to all piles. Furthermore, differential settlement of the pile tips appears to be inevitable, and it is unclear which part of the house will have piles with their tips in sand and which part in over-consolidated clay. Hence, it was suggested to make the research grid substantially smaller, as the current grid is too large to account for the observed lateral variability. Three more CPTs surrounding CPT020 were suggested. These additional CPTs should allow for a less conservative bearing capacity calculation. Whilst these additional data will not take away the need to account for differential settlement when dimensioning the above-surface construction, it will probably help constrain which pile tips will be in sand and which ones in over-consolidated clay.

The data suggest that there is no need to expand the ZOI.

Results of additional field work

The Ground Model was updated in order to include the three additional CPTs (Figure 28). The three CPTs are consistent with the earlier CPTs and help to constrain the exact boundaries of the different lithological units. The present data set is considered sufficient for composing the foundation advice. However, one should note that depending on the expected load on the piles and the associated pile tip depths, part of the house might have their pile tips in sand and another part in unconsolidated clay.

Figure 28. Cross-section based on the data collected for this project.



Source: Authors' own work.

Risks and mitigation

Table 10 summarises the risks identified and how these were reduced during the different phases of the project. Overall, the identified risks were sufficiently mitigated against by the end of the second fieldwork phase.

Table 10. Risks identified during the several projects stages, as well as their mitigation.

	Desk study	Field work phase I	Field work phase II
Risks	High lateral variability Peelo formation	Large differences between CPT 8 and 9 as well as 6 and 7	Additional CPTs help constrain presence of sand vs. potklei
	Unclear composition of compressible layers in top five metres	Undisturbed samples indicate these are not potklei	N/A

Source: Authors' own work.

Case 2: the construction of a road underpass (GC2)

Introduction

This project – a GC2-category example – concerns the construction of an underpass in the north-eastern part of the Netherlands under the ‘Middelberterweg’ (road) in ‘Middelbert’ (village). Figure 29 gives an illustration of the tunnel. The present road runs across the site and is bordered by ditches on both sides. Apart from this, the tunnel will largely be realised on former farmland. Some buildings are present close to the site (approximately 10 m). Most likely, these buildings will have a shallow foundation. Based on this, the underpass is considered comparable to a CC2 structure. The exact construction method has not been decided upon yet but will most likely involve constructing a sheet pile wall, drainage, followed by excavation. The maximum depth of the underpass is approximately 6.5 m – NAP and it is assumed that the bottom of the sheet pile wall will be at approximately 15 m – NAP. It is likely that the underpass will have a pile foundation.

Figure 29. Overview of the Middelberterweg underpass.



Source: Authors' own work.

Zone of influence

Provided sheet piling is be used (limiting the effect of dewatering on the surroundings), the zone of influence is determined by the method used for the sheet pile wall and the pile foundation and the associated vibrations. Hence, the ZOI is considered to be an approximate radius of 25 m surrounding the site, including all adjacent buildings and (underground) infrastructure.

Desk study

Data set

As very little data was available for the ZOI, a radius of approximately 250 m was used when collating the data set. This data set is summarised in Table 11. Little data are available for the area, many of the data points are dated and most boreholes are shallow. A geological voxel model for the area (100 x 100 x 0.5 m scale) was available.

Additionally, the following books were consulted:

- Berendsen, H. J. A. and Stouthamer, E., *De vorming van het land: inleiding in de geologie en de geomorfologie*, Koninklijke Van Gorcum, Assen, 2008
- Vos, P., *Origin of the Dutch coastal landscape: long-term landscape evolution of the Netherlands during the Holocene, described and visualized in national, regional and local palaeogeographical map series*, Barkhuis, Eelde, 2015

Table 11. Summary of available historical data, by source; the attained depth is in m below ground level.

Data source	Data type	Number of points	Attained depth	Date of execution
Company database (Geoloket)	CPT	14	<25 m	1999-2011
National database	Borehole	10	<7 m ⁽¹⁾	1990-2008

⁽¹⁾ B07D0352 goes down to 68 m

Source: Authors' own work.

Lithostratigraphy

The lithostratigraphic build-up of the area is summarised in Table 12.

Table 12. Summary of the area's lithostratigraphy.

Formation	Member / bed	Dep. Env.	Lithology	Depth interval (m NAP)	
				From ca.	To ca.
Naaldwijk	Walcheren m.	Estuarine	Clay, fine sand	Ground level	-4
Nieuwkoop	Basisveen b. / Nij Beets b.	Marsh	Peat	Ground level	-4
Boxtel	Undiff. / Wierden m.	Periglacial; fluvialite, aeolian	Sand, locally clay and peat	Ground level	-16
Eem	Undiff.	(shallow) marine	(Clayey / silty) sand, clay	-13	-33(*)

Notes:

The depth interval shows the approximate minimum and maximum depths between which a unit is expected to occur.

(*) Only based on one borehole

Source: Authors' own work.

Overall, the data indicate that most of the area is only underlain by a thin (<2 m) layer of compressible Holocene deposits, directly followed by the Boxtel sand (Pleistocene deposits). Several data points indicate that the Boxtel formation contains peat and (sandy) clay layers. The Eem, see Table 12, formation also contains several cohesive layers.

Recent history

This area has been a polder since at least since the early 13th century.

Topography

Ground level in the area is approximately at NAP to 2.25 m – NAP.

Underground infrastructure

Figure 30 shows the underground infrastructure that is known to be present in this area. As can be seen, a lot of underground infrastructure runs parallel to the “Middelberterweg”. Right at the site, some of these have a branch leading towards a farm to the southwest of the site.

Figure 30. Overview of underground infrastructure within the ZOI.



Note: Reds and browns: electricity; yellow: gas; blue: water; purple: sewage; green: data cables.

Source: Authors' own work.

Desk study – summary

The site has several points of attention, which should be addressed during subsequent stages. Firstly, with regards to infrastructure, the site intersects the 'Middelberterweg'. At the moment it is not known whether any compressible material is present under the road itself. This would be worth knowing, as any differential settlement between the overpass and the present road would be undesirable. Furthermore, the present road is bordered by two ditches. It should be made sure that the discontinuity in these ditches will not affect the drainage of the area.

Secondly, a substantial amount of underground infrastructure is present at the site. These will have to be relocated or accommodated for in the design.

Figure 31 shows a cross-section representative for the area. The lateral variability observed in the data should be able to be covered with a 25 x 25 m grid. With regards to the lithostratigraphy of the area, the following are of interest:

1. Thickness and composition of Holocene top layer, location of the top of the Pleistocene deposits

2. Presence and continuity of compressible and/or impermeable layers in Pleistocene deposits.

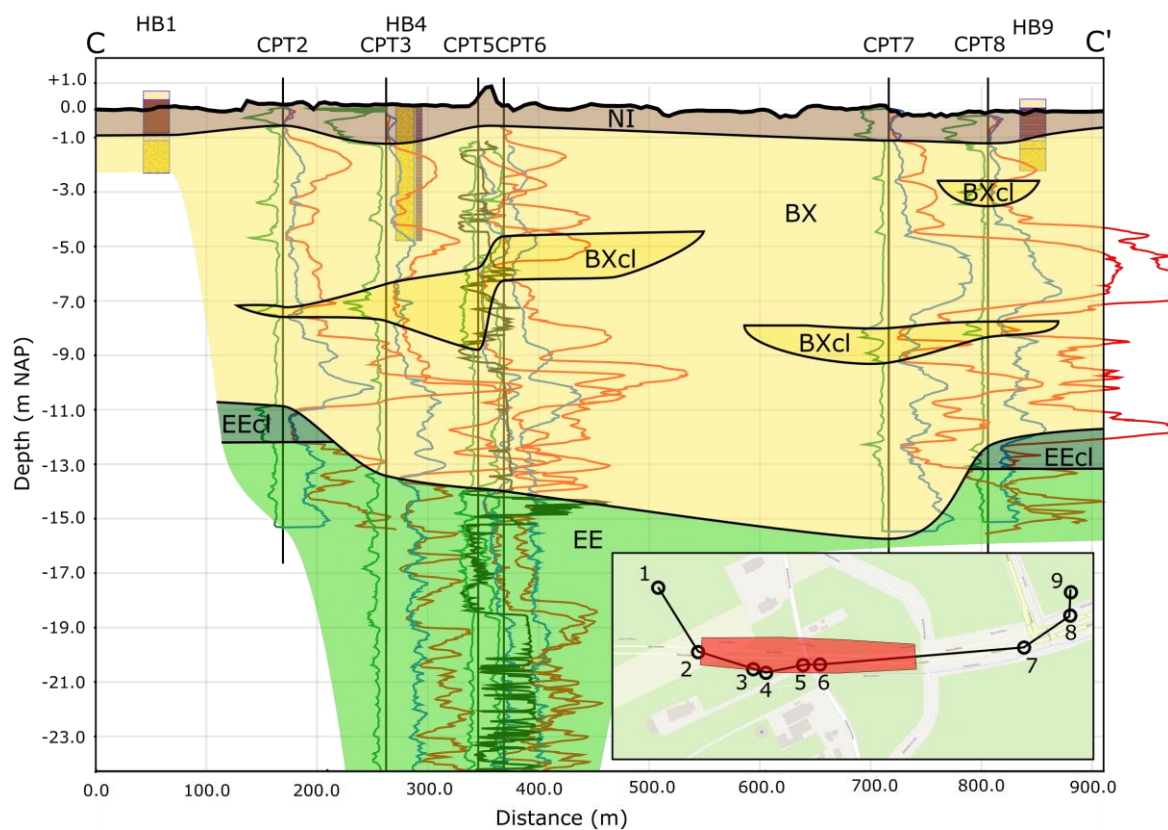
These two points will be elaborated upon below.

(1) This is worth investigating in order to determine how much compressible material is present at the site. This information can subsequently be used to plan the repurposing of the excavated soil.

(2) If no continuous impermeable layer is present below the site, the ZOI will have to be enlarged significantly or underwater concrete will have to be used. The present data suggests that there will not be a continuous impermeable layer within the Bostel formation, but it appears the sand of the Eem formation, see Table 12, is quite clayey below 15 to 17 m – NAP. Hence, for now the chosen ZOI appears to be appropriate.

Point (2) is also relevant with regards to designing the foundation of the tunnel, as the historical data indicates the presence of cohesive material right under the maximum depth of the underpass.

Figure 31. Cross-section made with historical data in the vicinity of the site (red area in map).



Source: Authors' own work.

Investigation plan

It was suggested to perform a combination of CPT's and boreholes with undisturbed sampling at the site. The CPT's would have to be made in an approximate 25 x 25 m grid, to at least 25 m below ground level. It was suggested to perform boreholes at approximately a quarter of the CPT locations, down to the same depth as the CPT's. The boreholes should be preferentially located at sites with cohesive Pleistocene layers. These undisturbed samples are initially meant for interpreting the CPT's but can later be used for consolidation tests and settlement calculations.

Fieldwork results

In the end, twenty-one CPTs and twelve boreholes were performed. These data were interpreted for their lithostratigraphy, which is summarised in Table 13. This table shows the range in top and bottom contacts, as well as the number of data points a unit occurs in. For several localities within the data set, both a CPT as well as a borehole was available; in these instances, the borehole was used to aid with interpreting the CPT. For example, the coordinates and contact depths from the CPT were considered as leading.

Table 13. Summary of lithostratigraphic units.

Formation ⁽¹⁾	Sub- unit ⁽¹⁾	Top Surface			Bottom Surface		
		min	max	n	min	max	n
AAOP		-1.2	-1.5	16	-1.5	-2.0	16
NA		-0.1	-2.2	25	-2.0	-5.0	23
NI		-1.0	-5.0	44	-1.7	-5.9	35
BX	C10	-1.7	-2.9	3	-2.0	-2.0	1
	WI	-1.4	-5.0	33	-3.8	-6.0	27
	s	-2.6	-10.5	29	-12.0	-17.0	26
	-cl1	-3.8	-6.0	10	-4.8	-6.8	9
	-pe1	-6.4	-6.4	1	-6.9	-6.9	1
	-cl2	-6.5	-6.5	1	-7.8	-7.8	1
	-cl3	-7.0	-10.0	16	-8.5	-10.5	16
	-pe2	-8.2	-8.8	3	-8.8	-9.2	3
	-cl4	-13.0	-14.3	2	-14.8	-20.3	2
EE	cl1	-12.0	-17.0	13	-14.8	-17.2	12
	s1	-14.8	-16.2	6	-16.5	-18.2	3
	scl	-12.8	-23.2	11	-17.0	-29.0	8
	-cl2	-17.0	-18.2	8	-19.2	-27.0	8
	-cl3	-22.8	-22.8	1	-23.2	-23.2	1
	-cl4	-28.0	-28.0	1	-29.5	-29.5	1
	s2	-25.8	-29.0	8		NA	

¹ Notes: AAOP = Antropogenic, NA = Naaldwijk, NI = Nieuwkoop, BX = Boxtel, EE = Eemien, WI = Wierden member, cl = clay, s = sand, scl = clayey / silty sand, pe = peat. It should be noted that for the Boxtel and Eemien formations, respectively the sand and clayey sand layers are considered as one unit. The sub-units marked by a hyphen are considered as occurring 'within' these two respective units.

Source: Authors' own work.

Interpolation method

IDW interpolation was performed for the top and bottom of each lithostratigraphic unit. The following modelling inputs were used: X boundaries at 582 680 and 583 020m, Y boundaries at 238 000 and 238 500, a 100-by-100 raster, a single-sector search radius of 25 by 25 m, a power of 1.2, a minimum number of neighbours of two and a maximum number of eight. When less than two data points were present within the search radius, the search radius was expanded until at least two data points were present within the search radius. An example of one of the layers in 3D is shown in Figure 32.

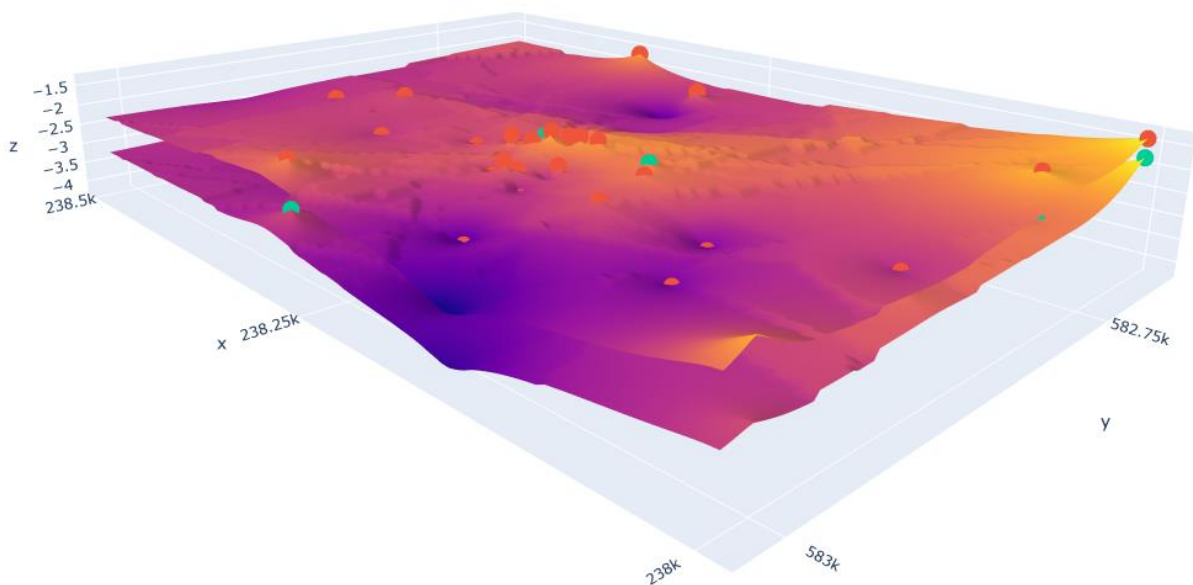
By subtracting the top Z value from the bottom Z value, the thickness was calculated. The thickness raster was used as a mask for the top and bottom rasters: for cells with a thickness of 0.1 m, the top and bottom cells were set to <null>.

Interpolation results

Several interactive 3D figures of the interpolation results were made, but unfortunately, these cannot be presented here. Instead, a representative cross-section (Figure 33) and 2D maps of the key units (Figure 34 - Figure 41) are presented and discussed here. The contours in the figures are at 0.25 m intervals, except for thickness maps where the smallest contour is at 0.10 m (if present), followed by 0.25 m, 0.50 m, etc. The black points denote localities that penetrate a unit's depth interval. Firstly, Figure 34 and Figure 35 show the top, bottom and thickness of the Naaldwijk and Nieuwkoop¹¹ formations. Overall, about a metre of cohesive material is to be expected.

Figure 36 to Figure 41 show the top, bottom and thickness of several cohesive layers, as well as the Eem formation clayey / silty sand. Overall, cohesive layers are to be expected to intersect with or lie right under the tunnel profile. Based on the present data set, several of these layers are (nearly) laterally continuous.

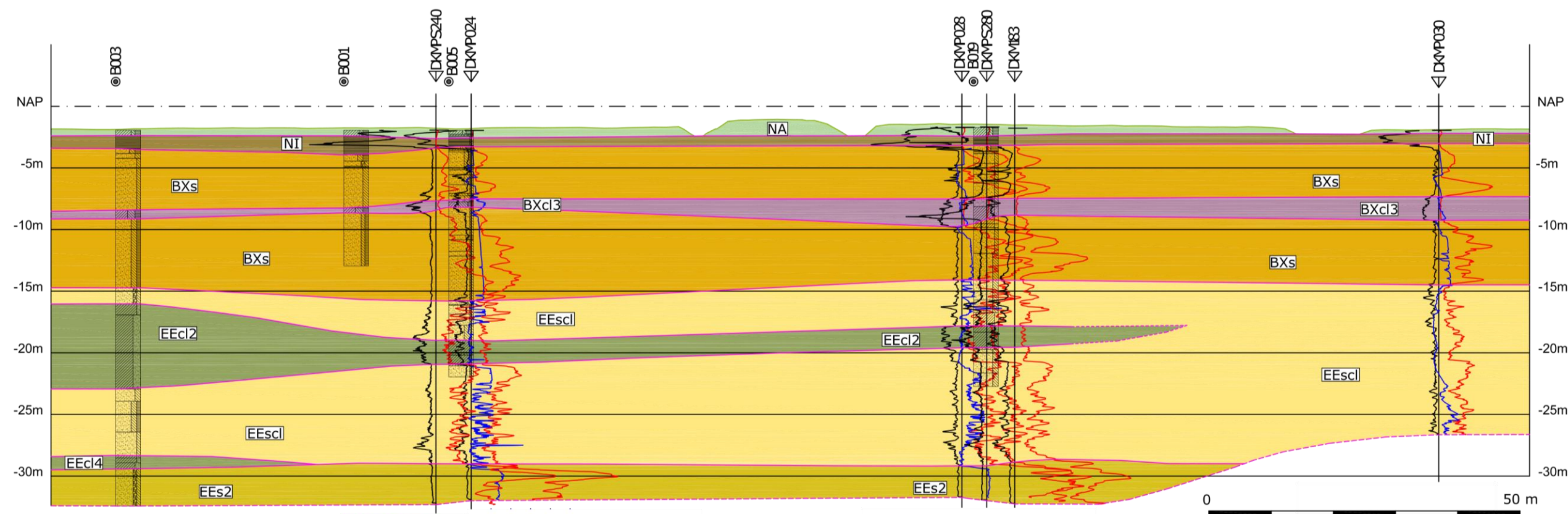
Figure 32. Example of the 3D model layer for the Nieuwkoop formation.



Source: Authors' own work.

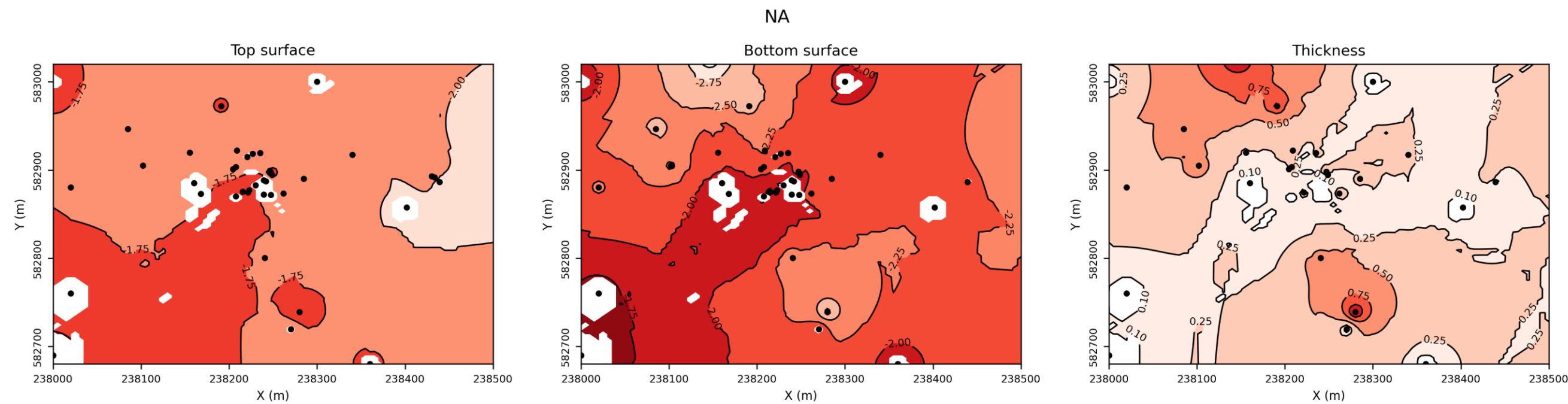
¹¹ The Dutch territory contains Late Pleistocene and Holocene sediments in the subsurface, with a shallow clay/peat layer of varying thickness belonging to the Naaldwijk Formation and Nieuwkoop Formation. The Southern Bight Formation, Nieuwkoop, and Naaldwijk are the subsurface Holocene deposits. The Nieuwkoop Formation is the Basal Peat Bed deposited in wetlands at the beginning of the Early Holocene sea level rise. The Velsen Bed of the Naaldwijk Formation was deposited in a shallow sea with lagoons that developed as the sea level rose higher above the ground.

Figure 33. Representative cross-section, running right through the middle of the site.



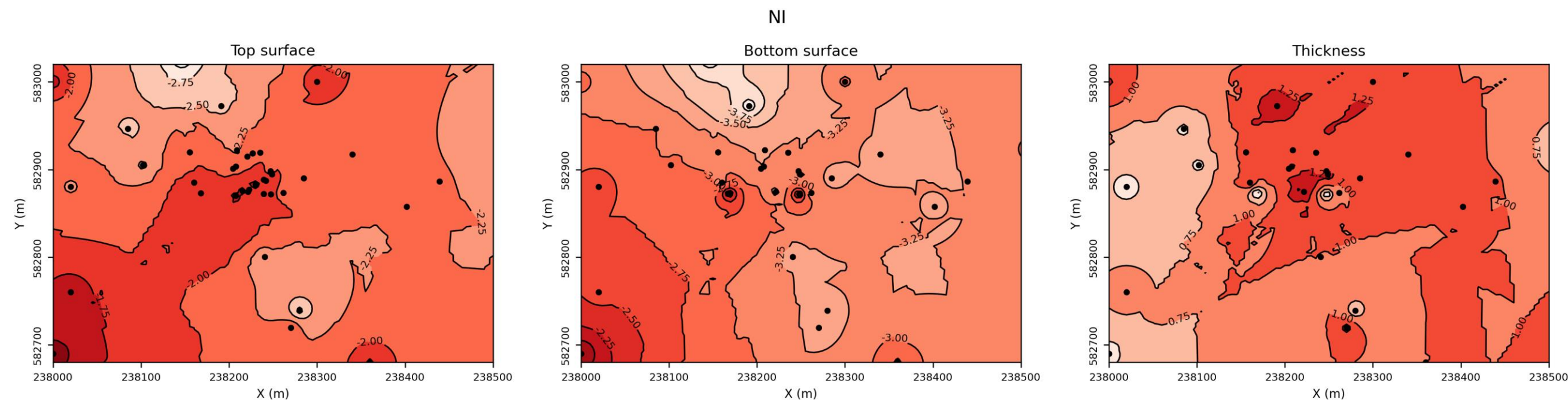
Source: Authors' own work.

Figure 34. Filled contour maps for the Naaldwijk formation



Source: Authors' own work.

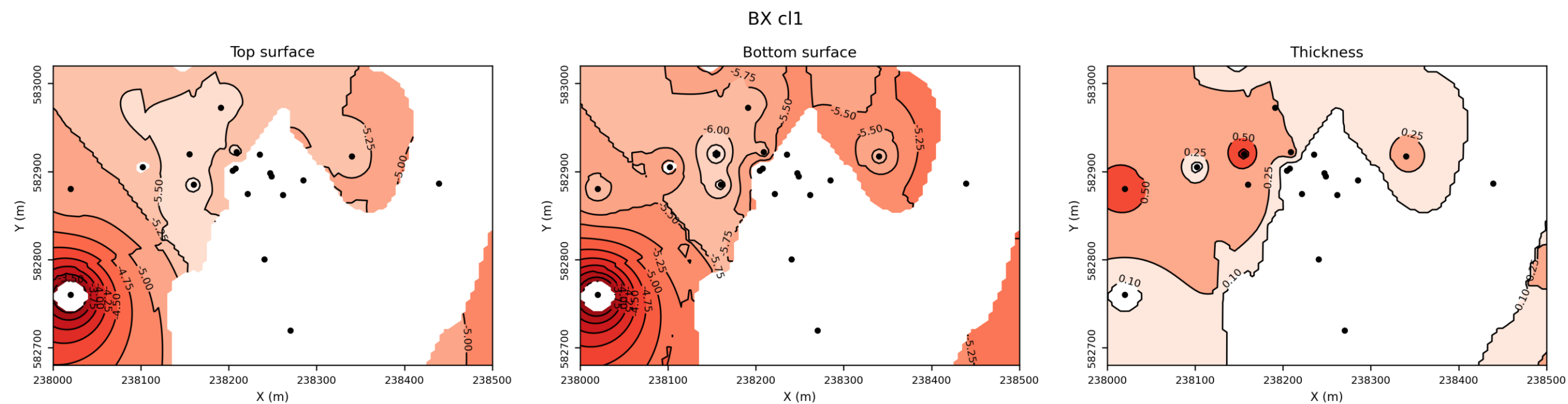
Figure 35. Filled contour maps for the Nieuwkoop formation.



Note: Contours are at 0,25 m intervals, except for thickness maps: here, the smallest contour is at 0,10 m (if present), followed 0,25, 0,50, etc. The black points denote localities, which penetrate a unit's depth interval.

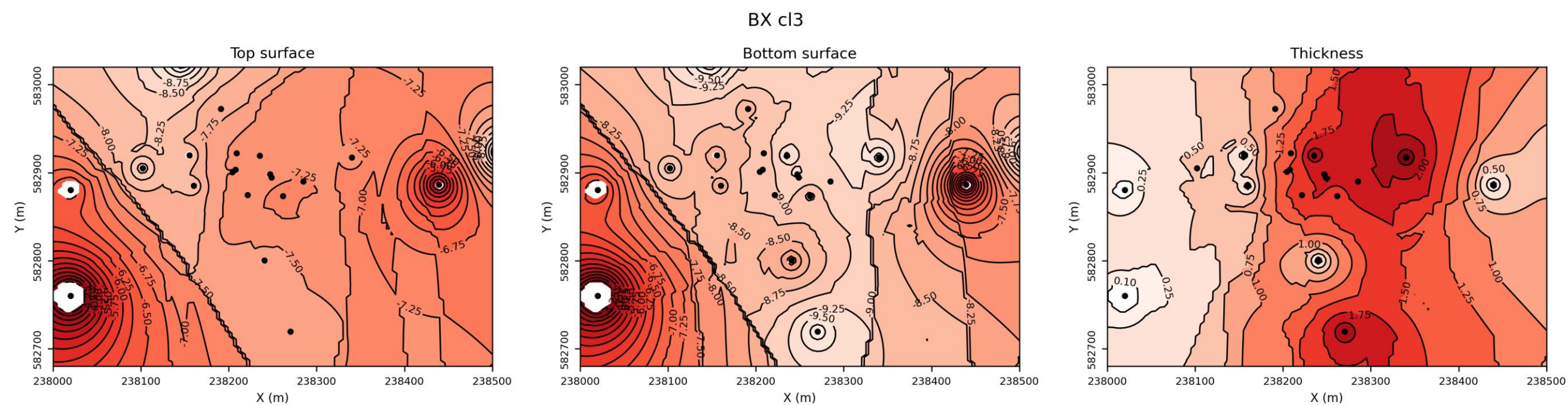
Source: Authors' own work.

Figure 36. Filled contour maps for the first layer of clay within the Boxtel formation.



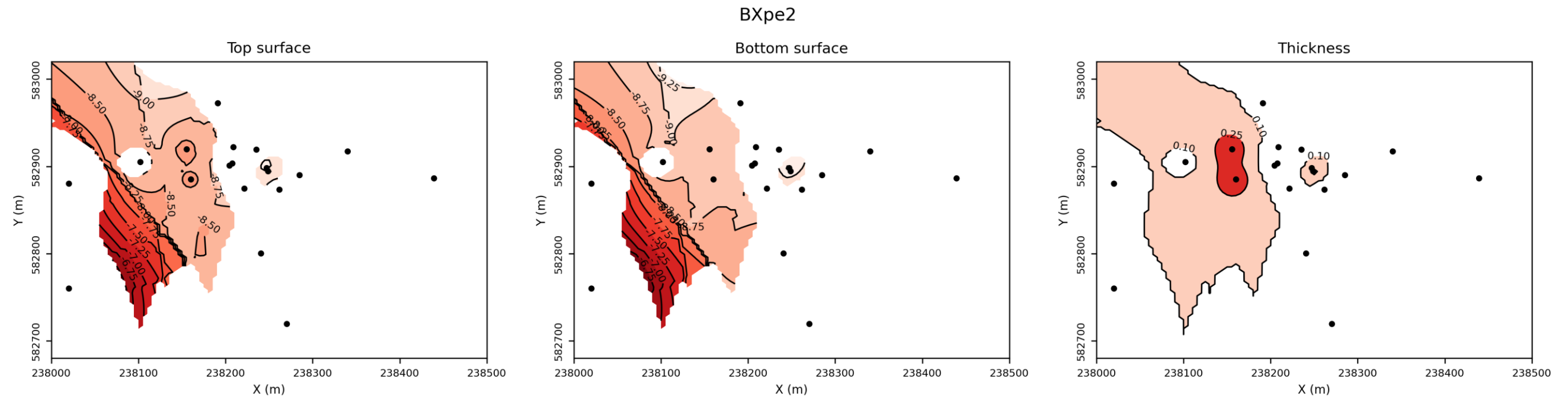
Source: Authors' own work.

Figure 37. Filled contour maps for the third layer of clay within the Boxtel formation.



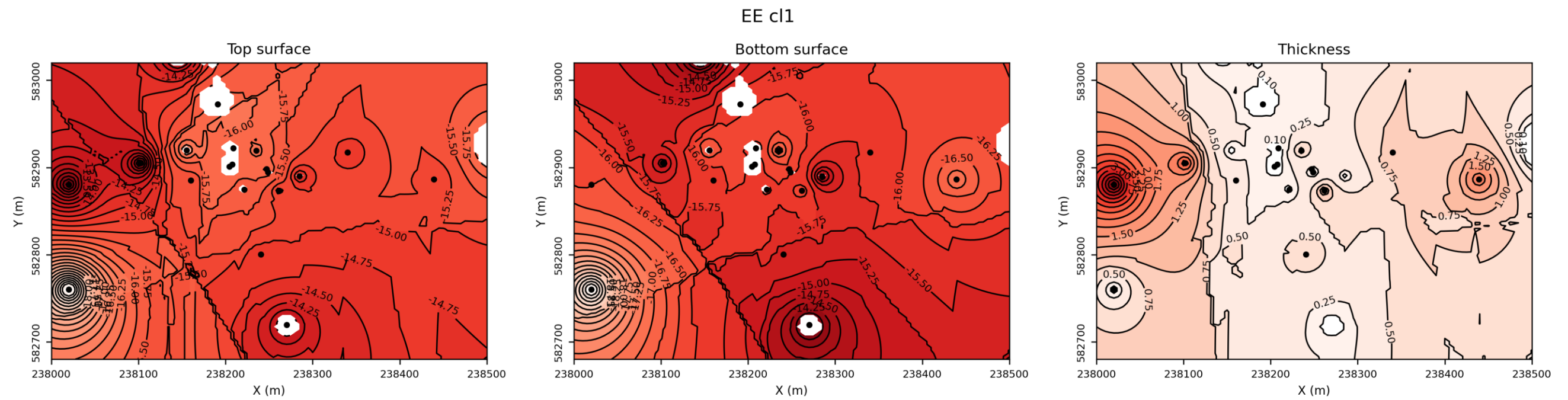
Source: Authors' own work.

Figure 38. Filled contour maps for the second layer of peat within the Bortel formation.



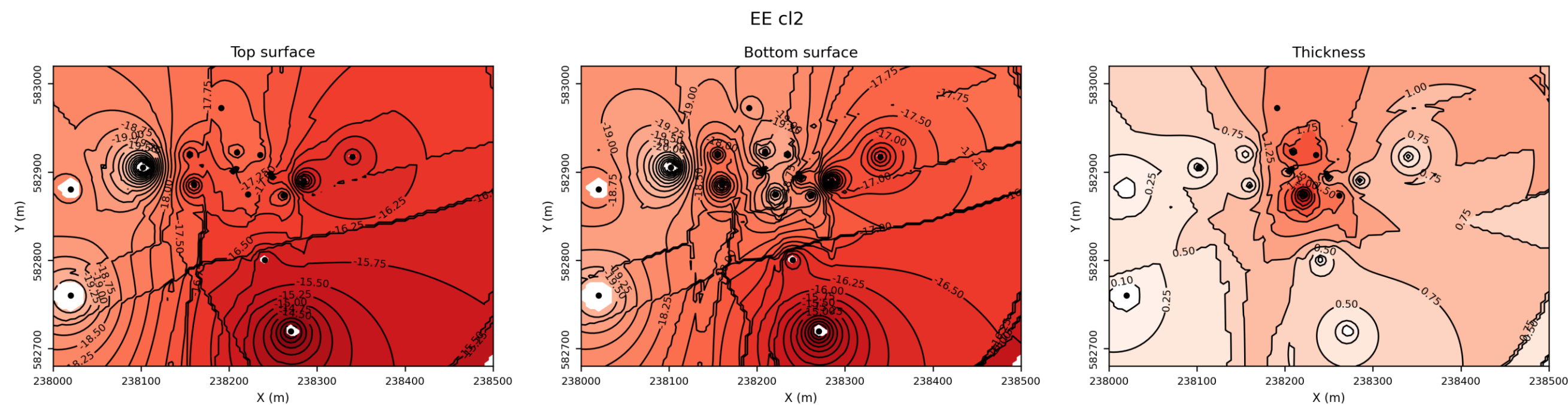
Source: Authors' own work.

Figure 39. Filled contour maps for the first layer of clay within the Eem formation.



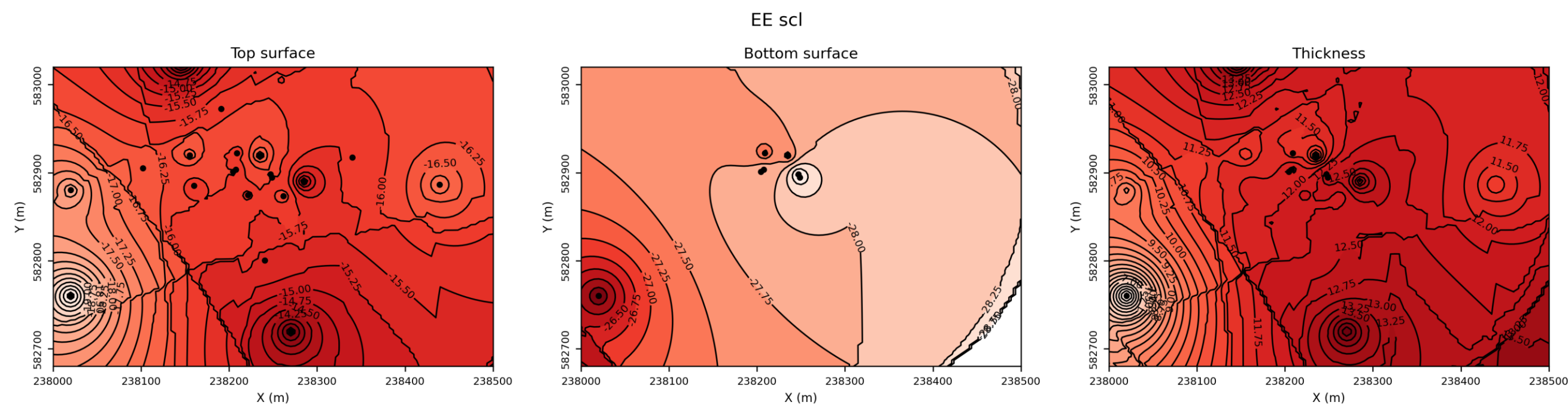
Source: Authors' own work.

Figure 40. Filled contour maps for the second layer of clay within the Eem formation.



Source: Authors' own work.

Figure 41. Filled contour maps for silty/clayey sand within the Eem formation.



Source: Authors' own work.

Discussion

The fieldwork has provided helpful additional constraints for the main issues from the desk study:

- About 1 m of Holocene cohesive material is to be expected
- Several cohesive layers intersect or lie right under the profile of the underpass.
- Several nearly continuous layers with a low hydraulic conductivity are to be expected within the depth interval of the sheet piling.

Based on these results, there is no reason to adjust the ZOI.

Risks and mitigation

Table 14 summarises the risks identified and how these were reduced during the different phases of the project. Several points are sufficiently constrained by the data. However, no research has been done on the soil beneath the 'Middelberterweg'. It would be advisable to perform boreholes and / or CPTs at the future bridgeheads. Furthermore, it would be advised to carry out a sensitivity analysis on the holes in the poorly conductive layers with respect to the drainage model. If the effect of the holes turns out to be very large, it is suggested to carry out additional CPTs in order to better constrain these holes.

Table 14. Risks identified during the several projects stages, as well as their mitigation.

	Desk study	Field work
Risks	Thickness and composition of Holocene top layer; location of top Pleistocene	Data sufficiently constrains these issues
	Presence and lateral continuity of compressible / impermeable Pleistocene layers	Data indicates presence of several nearly continuous impermeable layers
	Lithological composition of ground beneath Middelberterweg	Not constrained by data from this phase
	Presence of underground infrastructure	-
	Drainage of ditches bordering Middelberterweg	-

Source: Authors' own work.

Annex 2. Examples – Ground model for the Saint Joseph Bridge in Annot (France)

Introduction

The design of the Saint Joseph Bridge near Annot, in the Alpes-de-Haute-Provence region (France), is an example of a project that follows the Eurocode's requirements for ground models in rock engineering projects of geotechnical categories GG2 and GC3.

The new bridge will replace the temporary bridge that has been in place since 2012 and will be 57 m long, 10 m wide and will sit 45 m above the river Galange (Figure 42). The current road contains two sharp bends on either end of the bridge; the new structure will open up these bends, especially the one on the left bank (Figure 43 and Figure 44). The project includes excavation of the cliff side (left and right bank), new foundations for the abutments (left and right bank), anchors on the right bank, risk assessments and installation of rockfall prevention infrastructure.

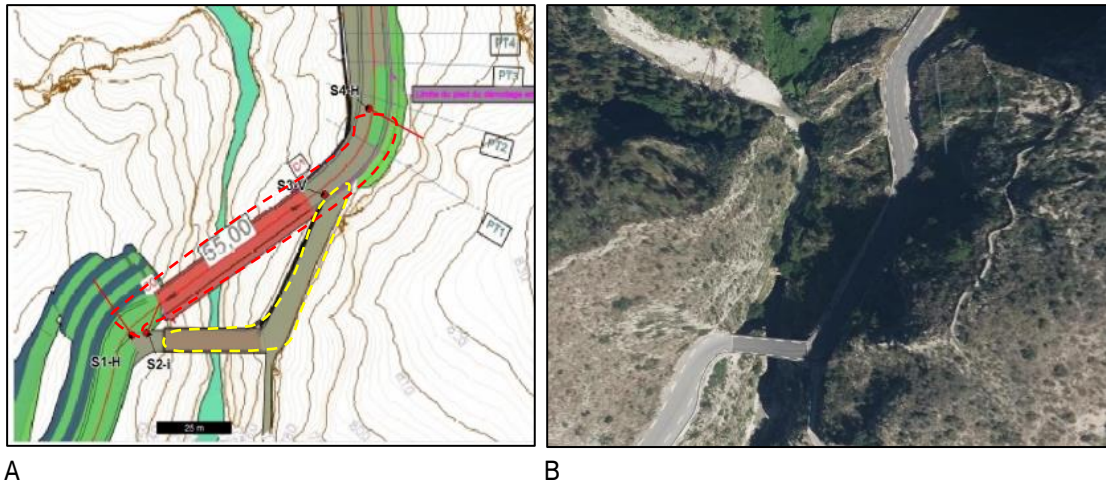
To successfully execute each one of these steps, it is necessary to have a thorough understanding of the site. Once enough information has been collected, it is possible to create a ground model. Special consideration is given to the definition of the geometrical properties of the rock mass, namely the rock discontinuities.

Figure 42. Map of France with Annot indicated in yellow (top) and study site for Saint Joseph Bridge located on a topographical map (bottom), in yellow.



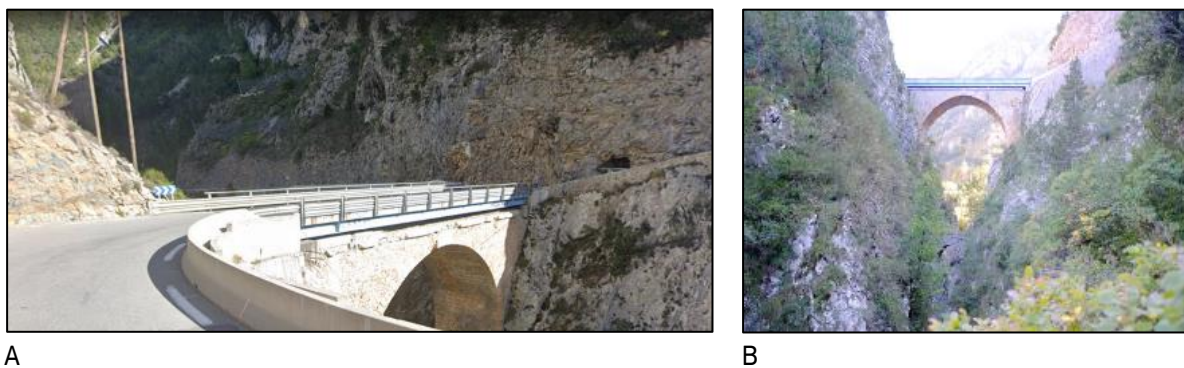
Source: Illustration by Scan 25, © IGN 2023 from Géoportail, le portail national de la connaissance du territoire (<https://www.geoportail.gouv.fr/>)

Figure 43. Diagram of the new and the old bridge structures. The new bridge is highlighted in red, and the old bridge is indicated in yellow (left). Aerial photograph of St Joseph Bridge (right).



Source: A) © D. Virely, B) Map data ©2023, Google Airbus from Google Earth <https://earth.google.com/>

Figure 44. General view of existing bridges from the left bank (left) and from downstream (right)



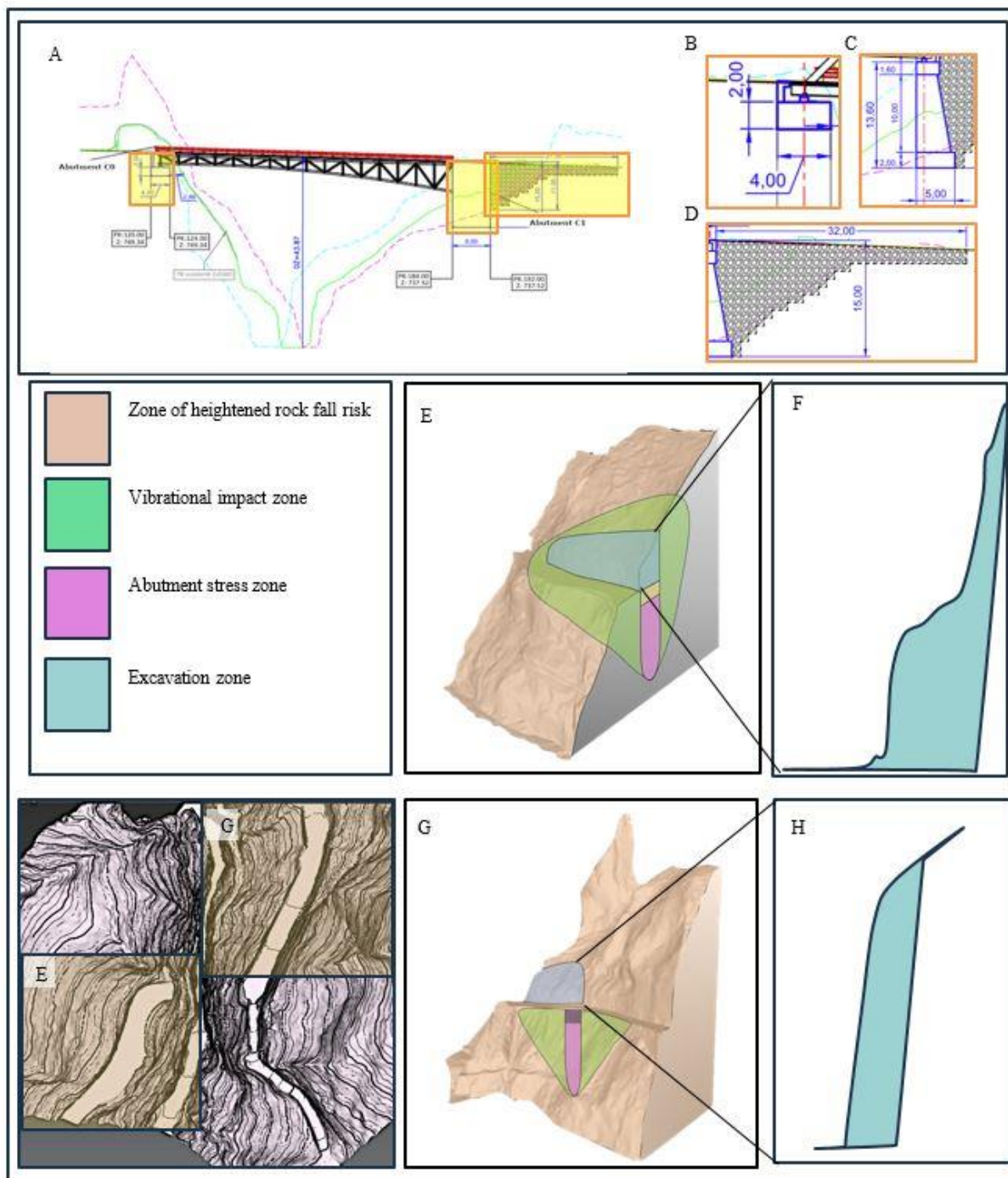
Source: © D. Virely, 2023

This ground model example is presented following a logical sequence based on EN 1997-2:2024, clauses 4 and 5 and on the diagram presented in Figure 1 of this Guideline. After the definition of the zone of interest, a summary of the main results of the desk study and site inspection and the anticipated Ground Model are presented. This is followed by the presentation of the main results of the preliminary and design investigations and by assigning a geotechnical complexity class to each zone of interest of the ground and obtaining their geotechnical categories. The verified Ground Model of this project is then presented, including schematic representations of the rock mass, including the discontinuities, and reference to the derived values of the rock mass properties that are relevant to the geotechnical design. Finally, a reflection on the further investigations needed for design is presented.

Zone of influence

The different parts of the civil engineering work for the new Saint Joseph Bridge allow the definition of specific zones of influence (ZOI) for each of them, as presented in Figure 45 and described below. The overall ZOI for the project goes from the rocky ridges upstream to the Galange's riverbed vertically and does not extend beyond the area of the road being worked on.

Figure 45. ZOI for the bridge, including a profile of the construction, a 3D representation of the ZOI and profiles of the excavation zones on the left and right banks (Note: Images A to H represent general terms, as described in the text below)



Source: Authors' own work.

ZOI for permanent infrastructure:

- Abutment C0 on the left side (Figure 45, B): 4 m long, 2 m high and 10 m wide
- Abutment C1 on the right side (Figure 45, C): 13,6 m high, 3 m wide (top), 5 m wide (base), 10 m long

- Gabion wall and lightweight embankment (Figure 45, D): 32m long, 15m high (left) 3m high (right)
- Rock bolting and or anchorage in the left embankment
- Beam anchorage on the right side of the river (the truss structure of the bridge will be built vertically and tilted over the Galange River, requiring an anchored beam for the pulleys used)

ZOI for Excavation:

- Left bank excavation (Figure 45, E, and F); slope angle and volume to be defined
- Right bank excavation (Figure 45, G and H): slope angle and volume to be defined

ZOI for temporary works:

- Earthworks and northern access to the slopes
- Earthworks and access to the right bank of the structure
- Vibrational impact zone (Figure 45, E and G)

ZOI caused by the consequences of the construction:

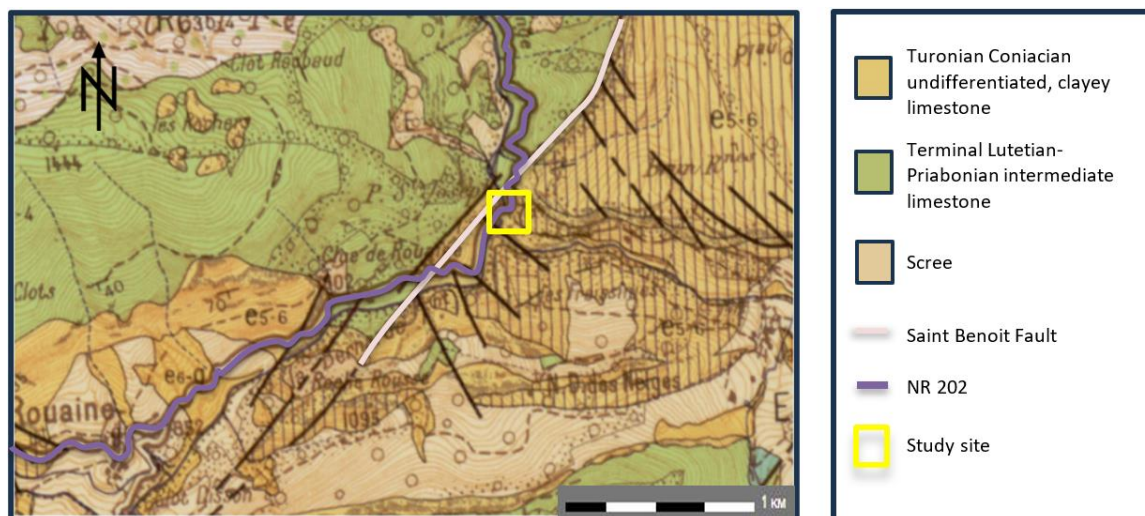
- Stress zone below the abutments (Figure 45, E and G)
- Influence of the construction works to the sustaining walls of the actual road
- Heightened rockfall risk zone (Figure 45, E and G).

Main results of the desk study and site inspection

At this early stage of the ground investigation, data were collected regarding several relevant aspects, namely the geology, the regional faulting, the seismicity of the area and the environmental impact of the construction works. A main aspect was to try to understand the rock masses involved and the discontinuities that intersect them. However, the only existing geomechanical data are from a vertical borehole drilled prior to the installation of the emergency bridge deck.

The geology of the site comprises of limestone, specifically Terminal Lutetian-Priabonian intermediate limestone at the site itself and more horizontally orientated Turonian-Coniacian limestone to the north-west of the site (Figure 46). The bridge spans the Galange Valley, connecting the two Eocene limestone escarpments (inclined at 70° on the right bank and at 50° on the left bank), 45 m above the river. The valley walls are exposed outcrops, except for the section beneath the road level. Both cliffs show dense fracturing with very slight stratification.

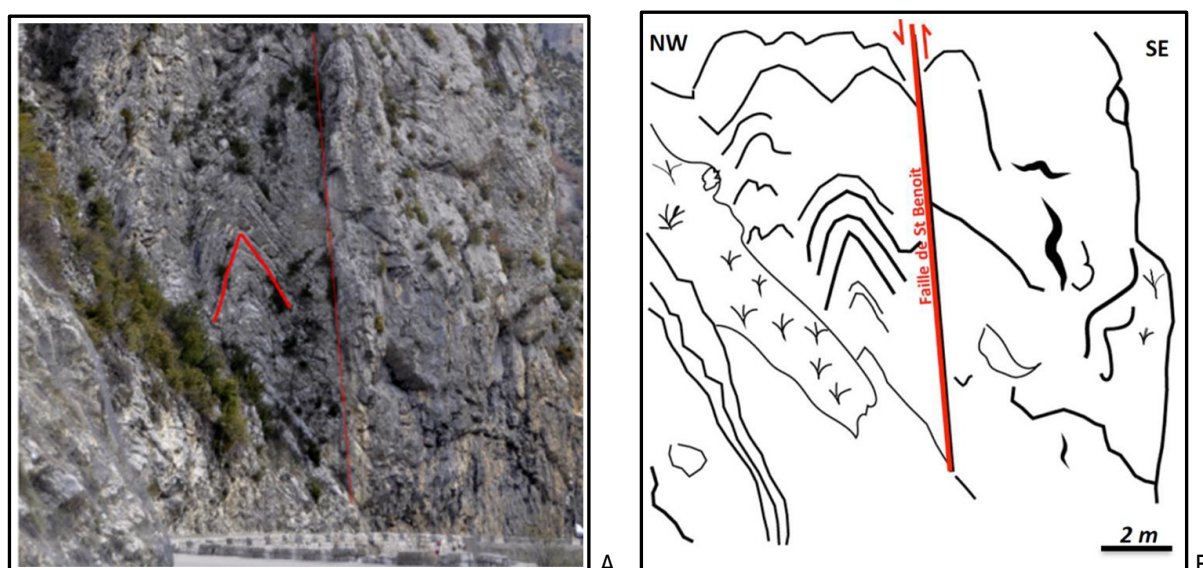
Figure 46. Geological map of the site and surrounding geology, highlighting the St Benoit Fault and National Road 202 (Geological map 1/50 000 (BRGM))



Source: Illustration by BRGM, 2024, © IGN 2023 from Géoportail, le portail national de la connaissance du territoire (<https://www.geoportail.gouv.fr/>)

The regional fault line ‘Faille de St Benoit’ (Figure 47) runs in an NE-SW direction with an orientation $N45^\circ$. It is visible on the embankment 1km upstream (North) from the bridge where chevron folding is observed adjacent to the fault line. The fault is classified as inactive. Despite this classification, the St Benoit Fault has been identified as having a potentially aggravating factor in local historical seismic events in 1855 and 1951. Due to the proximity of this regional fault to the study site, it should be taken into consideration when analysing its seismicity and the stability of the rock mass.

Figure 47. Photograph taken during the site inspection 1 km upstream of the bridge (A), displaying the ‘Faille de St Benoit’ and the associated folding (A, left) with a diagram outlining the main structural features. (B)



Source: Authors' own work.

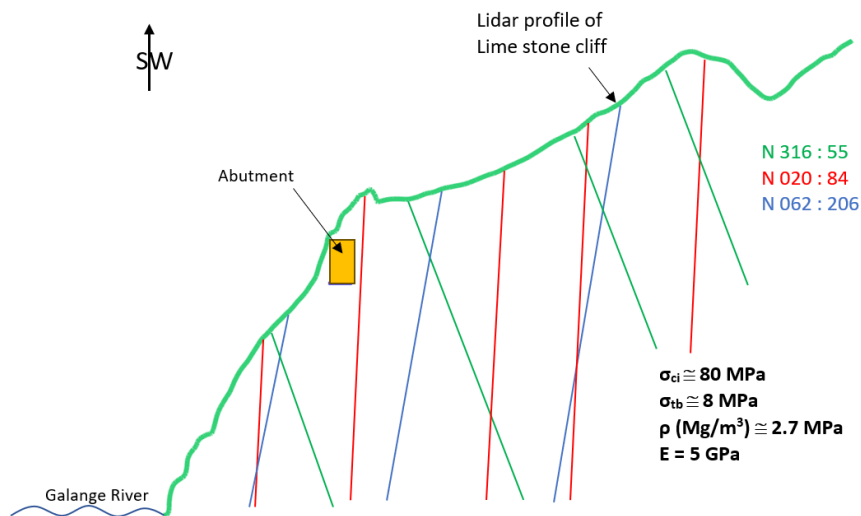
The bridge is in a level 4 seismic zone (see Eurocode 8), defined as ‘average’ on a worldwide scale. This is a relevant parameter for seismic design.

Due to the presence of certain bat and snail species near and beneath the bridge, the site was classified as type 1 according to French legislation. This is relevant because it implies that rock fall in the Galenge River during the construction works is restricted.

Anticipated Ground Model

Figure 48 presents the anticipated Ground Model obtained for the abutment on the left bank of the river after the desk study and site inspection. It includes a sketch with the slope profile and data on discontinuity sets and mechanical properties of the rock mass based on an existing Lidar profile and comparable experience. The desk study gave the orientations of the major discontinuities.

Figure 48. Ground Model at the end of desk study and site inspection.



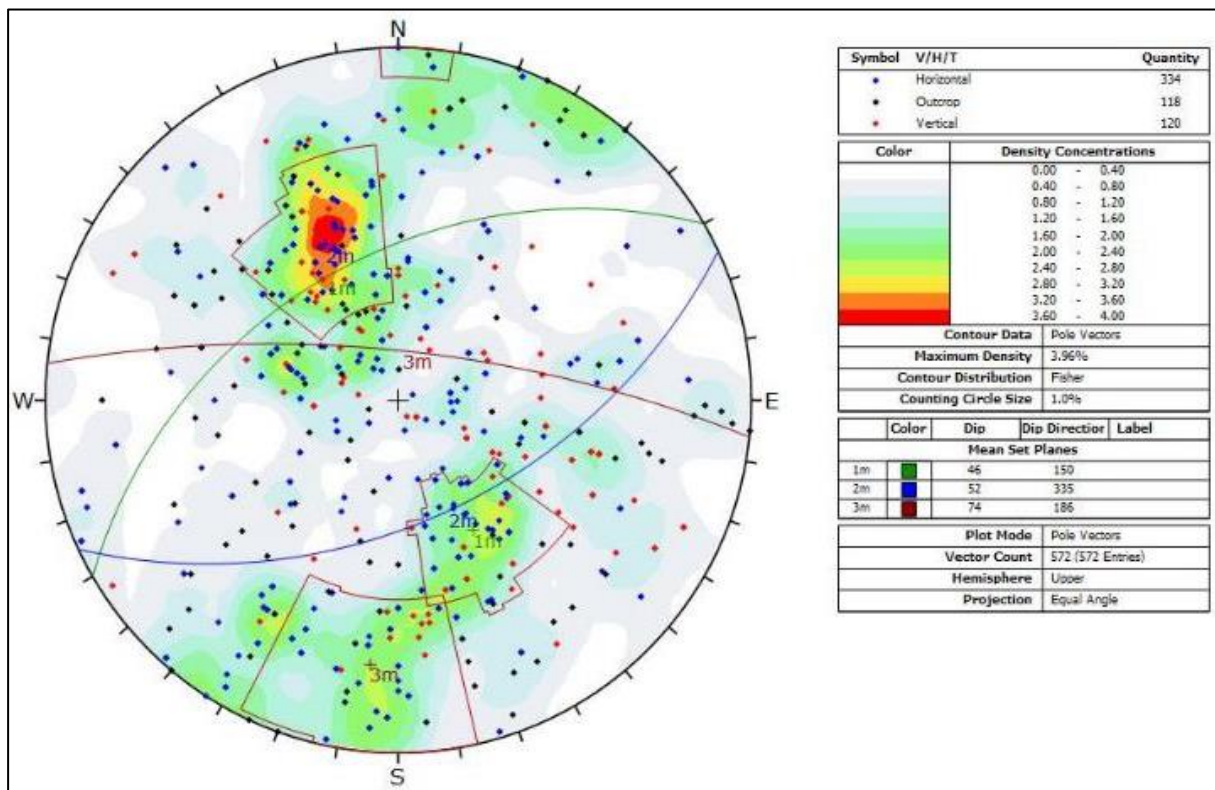
Source: Authors' own work.

Main results of the preliminary and design investigations

Preliminary investigation

A discontinuity survey was carried out, first with measurements at outcrops on both banks of the river. Subsequently, boreholes were drilled in the two banks, at several orientations to minimize sampling bias, and orientation measurements were taken using digital CCD camera images of the borehole walls. No significant variations were observed in the orientation of the joint sets from the left to the right bank. The combined orientation data from both banks, obtained from measurements in outcrops and boreholes are presented in Figure 49.

Figure 49. Stereogram showing the three main sets of discontinuities.



Source: Authors' own work

Three main discontinuity sets were identified, with the following mean orientations:

- Set 1: N 150: 45° (1m in the stereogram)
- Set 2: N 335: 52° (2m in the stereogram)
- Set 3: N 186: 74° (3m in the stereogram)

The digital Charge-Coupled Device (CCD) camera images of the borehole walls also indicated that the rock matrix can be considered homogeneous for the purposes of this project, except in the outcrops under the road on the right bank, where there is some surface alteration.

Design investigation

Physical, mechanical and geometrical properties

Laboratory tests were carried out to characterize the physical and mechanical properties of the rock matrix, namely the bulk mass density (ρ), the uniaxial compressive strength (σ_{ci}), the elastic modulus (E), the tensile strength (σ_t), the abrasiveness (also known as abrasivity) and the shear strength of rock discontinuities. In cases when many tests were performed, only some statistics of the values obtained are presented in Table 15.

Shear strength tests were carried out on three rock discontinuities, but only one was considered valid. A zero apparent cohesion was assumed, and the value obtained for the peak discontinuity friction angle was 45°.

Abrasiveness tests of the rock matrix were done on three samples, with minimum, mean and maximum values of 40, 80 and 100 g/Mg, respectively, which corresponds to a very weakly abrasive material.

Table 15. Statistics of the physical and mechanical laboratory test results

	ρ (Mg/m ³)	σ_{ci} (MPa)	E (GPa)	σ_t (MPa)
Number of samples	27	18	18	9
Minimum	2.65	58	14	8
Maximum	2.72	231	25	13
Mean	2.69	138	21	10
Standard deviation	0.016	47	3.2	1.9
Coefficient of variation	0.60%	34.6 %	14.9 %	18.0%

Source: Author's own work.

Rock Quality Designation (RQD) determinations were made from the borehole cores, to give an indication about the rock mass fracturing degree. Five determinations were made in one horizontal borehole, with minimum, mean and maximum values of 30, 44 and 70, respectively. Four determinations were made in one vertical borehole, with minimum, mean and maximum values of 10, 20 and 35, respectively.

Finally, measurements of the natural radioactivity in a borehole were taken, which showed that the discontinuities do not present a clayey infilling.

Dynamic properties

Several types of field and laboratory tests were performed to determine dynamic properties of the rock mass and obtain the 'Continuity Index' (CI), which is given as the ratio between the measured value of the compressive waves velocity (v_p) and the theoretical value for the rock type, which in this case is formed by calcite (6 259 m/s).

Two seismic refraction profiles were performed in one of the banks, resulting in the identification of two distinct strata: an upper stratum with $v_p = 2\,000 - 2\,200$ m/s and CI = 34% (1 to 5 m thick weathered rock mass); a lower stratum with $v_p = 3\,530 - 3\,730$ m/s and CI = 58% ('healthy' rock mass).

Micro-seismic borehole tests were performed in two horizontal and one vertical boreholes, resulting in values of v_p in the range 2 000 – 5 700 m/s, which give indications of zones with different degrees of weathering and/or fracturing.

Measurements of compressive and shear waves velocities (v_p and v_s) were performed in rock cores, in the laboratory. Some statistics of the values obtained are presented in Table 16. The mean value of the Continuity Index of the matrix is CI = 88 %, which corresponds to a very low level of micro-fissuration.

Table 16. Statistics of the compressive and shear wave velocities and of the dynamic elastic constants

	v_p (m/s)	v_s (m/s)	G_0 (GPa)	E_{dyn} (GPa)	ν_{dyn}
Number of samples	18	36	36	18	18
Minimum	5 094	2 599	18.3	52.4	0.23
Maximum	6 113	3 095	25.9	68.4	0.35
Mean	5 220	2 942	23.3	61.5	0.29
Standard deviation	326	123	1.96	4.03	0.03
Coefficient of variation	5.90 %	4.17 %	8.41 %	6.56 %	11,6 %

Source: Author's own work.

Values of the dynamic elastic constants were obtained from the values of v_p and v_s . Statistics of the dynamic shear modulus (G_0), Young's modulus (E_{dyn}) and Poisson's ratio (ν_{dyn}) are presented in Table 16.

Geotechnical category

Considering the results from the field measurements and the laboratorial tests, the geotechnical complexity classes for the different zones have been established. Its value is either GCC2 or GCC3, as can be seen in Table 17.

Table 17. Geotechnical category class and complexity class for each structure in the construction.

Zones	GCC	CC	GC
Earthworks and northern access to the structure	2	3	3
Abutment C0 on the left side	3	3	3
Abutment C1 on the right side	3	3	3
Earthworks and access to the right bank of the structure	2	3	3
Retaining wall/Reinforced embankment on the right bank	2	3	3
Temporary works (counterweight anchoring plates and support for the realization of the abutment weight C1)	2	3	3

Source: Author's own work.

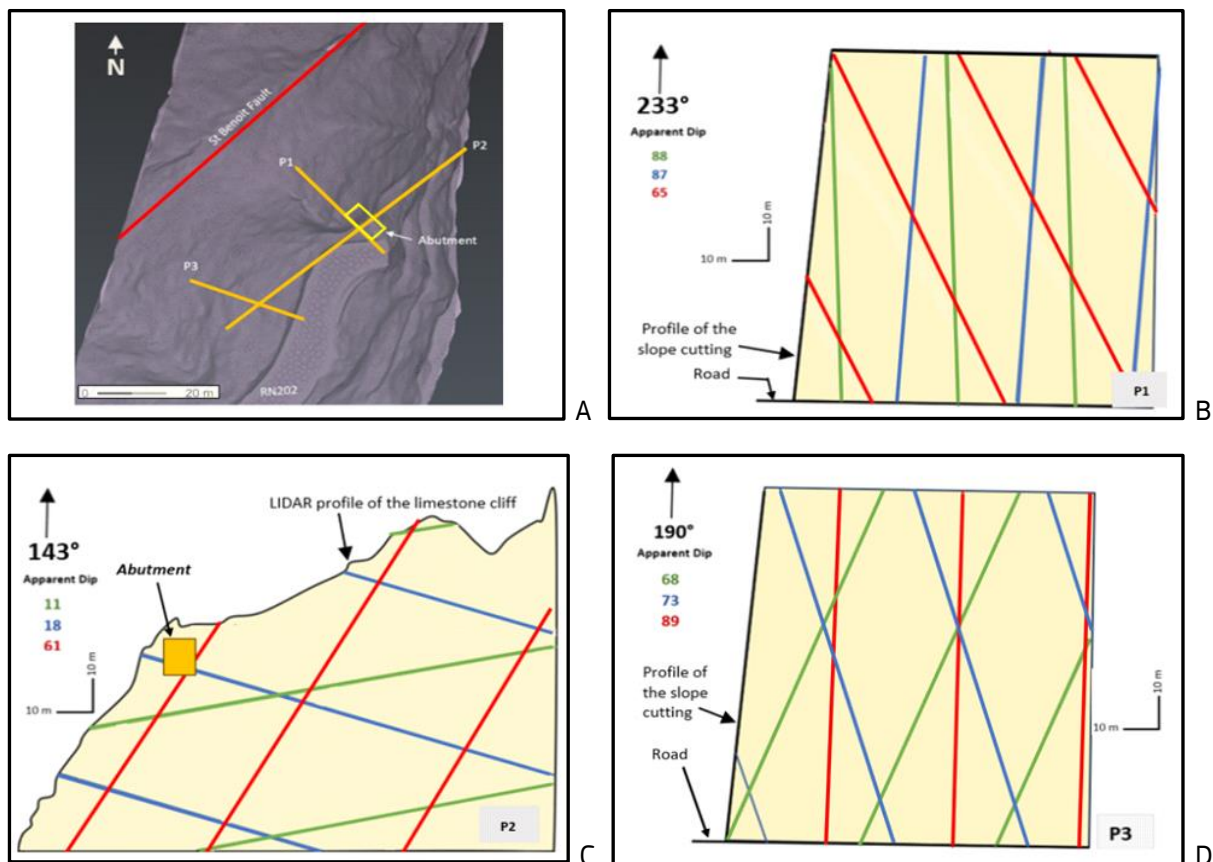
The consequence class for a national road in France is CC3 and, therefore, all structures that sustain the national road are classed as such. The combination of the values of GCC and CC gives the geotechnical category GC3 for all the zones of interest of the constructions works of the bridge (Table 17).

Ground model after the ground investigation

Schematic representation

Figure 50 presents schematic representations of the geometry of the Ground Model obtained after performing the field measurements and laboratory testing corresponding to the preliminary and design investigations. The geometrical properties of the rock mass, namely the St. Benoit fault and the three identified discontinuity sets are shown in the figure, for the left bank.

Figure 50. Ground Model displaying three profiles (A): P1 (B), slicing through the abutment, P2 (C), showing a slice along the abutment and P3 (D) slice south of the bridge. Each profile displays the apparent dip of the main discontinuities ⁽¹⁾.



⁽¹⁾ NB. The 2D sketches demonstrate the profile of the orientation on the apparent dip and should be considered together when planning the works.

Source: Authors' own work.

Derived values

The derived values are an important component of the Ground Model, and it is important to present, at least, the number of tests, the mean value and the coefficient of variation, so that the designer can make the necessary judgement to obtain the characteristic or nominal value of a ground property to use in the design.

The direct values obtained in the field measurements, the laboratory tests and by other means during the successive phases of the ground investigation, as well as derived values, were presented in a very concise way in sections 3 and 5. When they correspond to large numbers of tests or

measurements, instead of individual values, statistics of the whole set of values are presented. They correspond to the geometric, physical, strength and stiffness properties of the rock matrix and of the rock mass.

Final remarks

The Ground Model can have successive upgrades from the early stages of ground investigation. The Ground Model presented here is recognised not to be finished and, at later stages, additional ground investigation shall be performed, namely including the following:

- triaxial compression tests to obtain the failure envelope parameters (Hoek-Brown or Mohr-Coulomb) for the rock matrix;
- application of rock mass classification systems (GSI and / or others) to estimate the failure envelope parameters (Hoek-Brown or Mohr-Coulomb) for the rock mass;
- shear strength tests on discontinuities of the three sets at appropriate stress levels.

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