Reliability or Likelihood of Geological or Geotechnical Models

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Reliability or Likelihood of Geological or Geotechnical ($G^2$) Models

By

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Abstract

Nowadays, the likelihood of a subsurface geological model is becoming a very critical concern to geoscientists because the decisions on investments require accurate models and quantification of the economic and business risks.

The aim of this research is to build multi 3D models based on semantic approaches, and assess and evaluate factors affecting the reliability or likelihood of a geological or geo-technical model. The data set of the Reeuwijk road project, Western part of The Netherlands, obtained from NITG_TNO (Netherlands Institute of Applied Geosciences) has been used. The 63 shallow borehole data were selected covering an area of 3.2 km². Holocene and Pleistocene clay, peat and sand are the main sediments. By an integration of geo knowledge acquired from multiple data sources such as previous reports, geological and geo-technical maps and sections, the conceptual framework has been designed for guiding interpretations of the down hole data in assisting the modelling process. In the course of the modelling approach, different possible ways of presenting the lithology units and lithostratigraphic formations were used and as a result four different types of models have been produced which each can be used for different purposes, and are executed by the lithological modelling and stratigraphic modelling respectively in Rock works 2002.

In this research work, methodology is formulated that could help in the evaluation of the likelihood of the G² models. These might be pursued by two ways: one qualitative and one quantitative.

1. Visual inspections through a logical reasoning system of an expert having a good geological knowledge of the area and/or comparison of the made models with an existing references data set. Especially user-defined modelling objectives can help and ensure that the final model output is compatible with its intended applications.
2. A conceptual design of reliability assessment methodology is proposed to select or rank (in terms of reliability) the models based on the quantification of the input parameters, such as data quality, interpretation quality and quality of modelling algorithms. The evaluation of the likelihood of a model requires conversion of the subjective reasoning or logic to mathematical computation, to obtain a likelihood index. This is executed in a four-step process.
   ✓ Step 1: To define the modelling objectives properly and establish the standard format which can satisfy the idea of professional experts
   ✓ Step 2: To gather the opinions from different professional experts by questionaries
   ✓ The third step is to organize different opinions systematically and assign the weighting score for each parameter either by the verbal method or statistical methods
   ✓ The fourth step is to sum up the reasoning result from the data quality, interpretation quality and modelling parameters, and give the final ranking of the model.

In this research, the second part is not fully covered because it requires a lot of time and resources.
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1 Introduction

1.1 General

About 90 percent of valuable natural resources are located below the ground and about 80 percent of geo-hazards originate or are initiated directly or indirectly by endogenic processes. Monitoring the progress and intensity of these processes and utilization of the resource for development strategies and environmental management requires exploitation of subsurface information.

Various researchers have contributed to geosciences modelling in different geo environments, but the reliability of the constructed models cannot be defined and no definite rules and regulations are available to quantify the degree of reliability.

Though the traditional geological model is usually represented by orthogonal projection on to a 2D plane as a series of cross-sections and maps, the information in the third dimension can be presented indirectly using isolines, structural symbols, etc. Traditional geologic maps, which show the distribution and orientation of geologic materials and structures at the ground surface, have served for many years as effective tools for storing and transmitting geologic information (Jachens, et al., 2001).

The introduction of Geographic Information Systems (GIS) enhanced traditional geologic maps in terms of ease of use and communication of geologic information. In addition, GIS capabilities, advances in computer hardware, and geologic modelling and visualization software now provide possibilities to construct 3D subsurface geological models. The degree of accuracy and reliability of subsurface models constructed from the same data varies from person to person involved in the reconstruction based on cumulative experiences at a particular site or field. According to Orlić, (1997) as the geological pattern becomes more complex and the amount of data increases, the spatial reconstruction, although possible, becomes a tedious, time consuming and error prone process.

Geo Modelling can be engaged in two broad applications namely geometric and property modelling. Modelling of geometry defines the shape, size and location of geo-objects, where as property modelling includes the spatial variability of the geotechnical property of the geo-object under investigation.

1.2 Research problem

The likelihood of subsurface geological models is becoming a very critical concern because geoscientists need to have complete knowledge in time and space, of the system of interest. The geological properties of soil and rock masses are generally variable in vertical or horizontal dimension and often also in time. Geo Models are constructed normally in an attempt to represent the system (geo object) and its behaviour based on interpretation of observations and measurements of the system. Considering the earth material as a homogeneous or isotropic ob-
ject might be scale dependant and is governed by the objective or the importance of the project. This ambiguity can account for the creation of unreliable geo science models. In addition, because of uncertainty in data acquisition, interpretation, and model parameters, in most cases, the models constructed by various professionals from the same data are different.

The model may not be accurate and not a true representation of reality even when done by the experienced geologist. According to Hack, (2003), in nature there is no absolutely accurate model to be built, even if the project is finished, the model used may not completely reflect reality. Generally, the accuracy of a model of the sub-surface will be based on a balance between improved details against higher costs. Even then, a three-dimensional model can never represent the real situation; it can indicate spatial association and relationship with variations of properties in vertical and lateral extension, and time.

Research questions:

1) Could a methodology be defined to verify uncertainty model during an interpretation process for 3D subsurface model construction using a semantic approach?
2) Does the constructed Geo knowledge reasoning framework assist an interpretation process for building multi models?
3) Do multi model results give an alternative solution for different possible scenarios?
4) Can the reliability of subsurface models be quantified through the establishment of a likelihood index?

1.3 Objective

The aim of the research is to perform an integrated geosciences data analysis to build multi 3D models based on semantic approaches and assess likelihood of geological or geo-technical model.

The specific objective of the research is:
- To apply a geological knowledge framework for guiding interpretation processes creating multi models based on the designed criteria or parameters.
- To validate multi models with 10% of a data set remaining (not used in the modelling process), and
- To assess and evaluate factors affecting reliability or likelihood of geological or geo-technical models.

1.4 Data sets for the research

The available borehole data set of the Reeuwijk district, the Netherlands is selected for a study purpose. The data set was obtained from previous master research material, Amurane (2003), originally from TNO-NITG. The Reeuwijk district data set covers more than 91 km² area and 1000 bore hole data are available, only 63 boreholes were selected in this study due to the limited study time. The area covering a total of 3.2 km² with an approximate size of 1.6 x 2 km is selected in the north-eastern part of the area, across the main highway (A12).
The Reeuwijk District is a polder area located in the province Zuid Holland in the central western part of the Netherlands. According to Amurane (2003), the area is a geologically deltaic environment and consisting predominantly of Clay, Peat and Sand having a large variation in engineering property. Most of the soils are either, fluvial or marine in origin. The area is flat terrain lying at an average of –1.6 m NAP (National Mean Sea-level Reference).

1.5 Structure of thesis

The thesis comprises of eight chapters:

Chapter one introduces the general status in the field of 3D subsurface modelling, and applications in different geosciences disciplines. Research problems and questions to be raised, the objectives and data set to be used.

Chapter two presents a literature review about the likelihood of 3D have progressed surface geological and geotechnical problems and investigates how far different authors involved in this field what methods applied in solving the problems exist, and also assess the sources of uncertainty in data handling, process and visualizing.

Chapter three discusses about the research method including approaches for evaluating reliability of Constructed models and procedures followed to tackle the problems.
Chapter four summarizes the background information, based on opinions of various researchers about the geology, geomorphology, geo-technical and ground settlement problems of the study area.

Chapter five presents the application of rockworks 2002 software, the building of multi models from lithology, geology based on the constructed framework for guiding interpretation process of the data. Geometry and property modelling construction based on different data size and modelling resolutions are discussed.

Chapter six discusses comparison of multiple 3D subsurface models constructed on different data sizes, resolution and algorithm. Comparison criteria based on different parameters are also presented.

Chapter seven introduces an assessment of a likelihood of models. Factors involved in the likelihood index and proposed methods for generation of likelihood assessment and input parameters are incorporated in the possible methods to assess a level of reliability of models.

Chapter eight discusses the findings in this research activity and suggestions for further research.
2 Literature Review

2.1 Introduction

In this chapter the author reviews and discusses parameters and elements involved in the influence of difficulties in modelling and evaluation of reliability or likelihood of geological models.

Various researchers have contributed to geosciences modelling approaches and there are different methods available for geoscience modelling but the reliability of models is not fully understood and no definite rules and regulations so far are available to quantify the degree of reliability.

Whether the end objective is waste site characterization, contamination assessment, ground water flow simulation, mineral resource evaluation, reservoir engineering or tunnel design, the common denominator for geoscientists is a concern with investigating and characterizing the geological subsurface (Houlding, 1994). Though the target for the geoscientist is to conquer the subsurface information in utilization for planning strategies and resource evaluation or controlling natural and anthropogenic processes for natural hazard assessment and decision-making, the Constructed models are not always fully representing the real situation or specific geo-object.

According to Pilouk (1996), there are two kinds of firstl world objects and these may be differentiated in terms of prior knowledge about their shapes and location. Objects having discrete properties or with known or well-defined spatial extent, location and properties such as buildings, road, bridges, land parcels, fault blocks and perched aquifers; the second category are objects with various properties that can be defined by means of classification using property ranges; for example, soil strata may be classified by grain-size distribution, moisture content, and pollutant elements in the water by percentage ranges and so forth.

Availability of high capacity computers and friendly accessible software facilitated the development of geo-science modelling. Even though computers facilitate routine works and organize extensive data, the modellers should use or perform judgment in the analysis and evolution of input data and interpretation. The final computer generated model, which may seem beautiful, can be “garbage” derived from a “garbage” source and the result may not be better than that done by traditional ways.

2.2 Modelling Approaches

Different methods are available to create 3D subsurface models from the available data. Commonly, the modelling approach can be divided in to two categories: volumetric and property modelling.
Note that, the detailed description of each kind of modelling approaches can be read from Turner (1992, 2003), Orlić (1997), Houlding (1994, 2000), Staffhorst, (2001), Gerritsen (2000), and Raper (2001) etc. Below the the main modelling approaches are simply described.

### 2.2.1 Volumetric modelling

Volume modelling of the sub surface can be performed via surface based modelling Houlding, (1994). Surface based volume modelling is particularly appropriate in relatively simple geological situations. According to Houlding (2000), volume modelling can be done in layered stratigraphy, where the geological or geo-technical units to be modelled are situated between irregular surfaces. Geological models can be rapidly created in the form of prisms, between triangulated (TIN) surfaces representing stratigraphic or surface information (Lynx, 1997). According to different researchers volume modelling can be performed based on Surface-based grid modelling, geostatistical method and stochastic simulation.

### 2.2.2 Property modelling

Modelling property is referred to as the spatial estimation of the properties under study such as mineral grade, geo-technical properties (unit weight, permeability, porosity, etc). The estimation of properties is commonly performed on a set of nodes (grid model or block model) defined within the geo-object. The nodes represent either the centroids or the vertices of the volume primitives in to which the geo-object has been tessellated.

Several methods are available for property estimation, such as inverse distance with power, kriging technique, geo-statistical simulation etc. The selection of the estimation approaches depends on the quantity and quality of the data set, the spatial variability of the property under study and the objectives for which property estimation is performed. The methods of kriging and geostatistical simulation are introduced as follows:

#### 2.2.3 Kriging

Kriging is a linear interpolation method, which provides an estimate of the property as well as measurement of uncertainty associated with the estimate. Any sampled location can be estimated based on neighboring measurements, but the estimated value may depend on the distributions of sampling and quality. This approach has its application assumptions i.e., the data distribution falls in the normal or logarithmic distribution.

#### 2.2.4 Indicator kriging

Indicator kriging is a non-parametric technique, which provides risk-qualified estimates of unknown values Journal, (1983) in Orlić 1997. According to Houlding (1994), indicator kriging is primarily concerned with predicting the spatial variation of the probability of the variable meeting specific criteria; for this reason the technique is also referred to as probability estimation technique.
2.2.5 Geostatistical simulations

Geostatistical simulations represent a stochastic technique for assessing the impact of uncertainty in subsurface modelling. The fundamental difference between kriging and geostatistical simulations is that kriging produces a single best answer in a local sense where stochastic simulations provide many alternative realizations, each of which is a good representation of reality in some overall sense.

2.2.6 Stochastic modelling

This approach can be used for modelling both geometry and property under study. The word stochastic is derived from the Greek language and has a meaning ‘random’ or ‘chance’ where as the word deterministic has the meaning ‘sure’ or ‘certain’. A deterministic model predicts a single outcome from a given set of circumstances. In stochastic models a set of initial circumstances doesn’t always lead to the same outcome, there is no deterministic regularity. Stochastic models predict a set of possible outcomes weighted by their likelihood or probability of occurrence; Taylor and Karllin, (1994); Damsleth, (1990)

Stochastic modelling is mainly applied in the field of petroleum industry especially in the field of reservoir characterization, due to many failures in predicting oil field performance using oversimplified and unrealistic geological models created with conventional modelling techniques. Conventional models often show layer cake stratigraphy and too little complexity between the bore holes (Srivastava, 1994).

The scarcity of well data and the inappropriate use of these data, e.g. linear interpolation between widely spaced wells does not give a realistic image of the heterogeneity of the subsurface, therefore stochastic modelling techniques and geostatistics have been developed to give a realistic description of the spatial variation of the subsurface (Bratvold et al., 1994).

Haldorsen and Damsleth (1990) distinguish six main reasons to apply stochastic techniques to subsurface heterogeneity modelling.

- Incomplete information about dimensions about internal (geometric) architecture and property variability on all scales,
- Complex spatial disposition of subsurface facies,
- Difficult to capture property variability and variability structure with spatial positions and directions.
- Unknown relationships between property value and the volume of material used for averaging (scaling problem).
- Relative abundance of static (point values along a bore hole) over dynamic (time dependent effects) subsurface data
- Convincence and speed
Although stochastic methods, at first sight, may seem easy to use, they require the user to provide quantitative information about facies and parameters such as geometry, trends, stacking and repulsion. These parameters may be difficult to extract from the measured field data, and users must prepare to input information on analog data as well as on general knowledge and experience. Stochastic modelling doesn’t simplify the modelling task but provides more consistent and realistic, and therefore better results (Bratvold et al., 1994).

### 2.3 Representation and visualization of Geo-objects

There are different ways of representing geo-objects. Representation is based on the point of interest or objective of the study. Commonly used systems are based either on:

- Mode of visualizations in terms of dimensionality of the spatial objects, this can be as point (0D), line (1D), surface (2D), and volume (3D)
- Mode of occurrences as surface and subsurface, and
- Stage of modelling (Prior, Syn, and posterior)

In the mode of representation of the geometric surface (Girding and boundary), volume (block), property model geo-scientific data visualizations can give a clue to the interrelationship and the position of the geo-object in its extent with its respective views.

Visualization approach of geo-object has been defined by Tufte (1990), as a cognitive art but Keller (1992) applied the term to the study, development, and use of graphic representations and supporting techniques that facilitate the visual communication of knowledge.

For complete understanding of the subsurface geo-object, either the shape or volume visualization very important for planning for further assessments. Figure 2-1 presents the visualization mechanisms and processes of the geo-object starting from an available data set, exploration of information, analysis of the data and presentation of shape and volume of the geo-object.
2.4 Uncertainty and likelihood of Models

Different people use the word uncertainty differently; most people take uncertainty as a primitive term whose meaning is accepted but is undefined. Christian (2003) distinguishes three facets to the notion of uncertainty:

- Uncertainty with respect to facts means that an outcome is unknown or not established and therefore in question.
- Uncertainty with respect to a belief means that a conclusion is not proven or is not supported by unquestionable information.
- Uncertainty with respect to a course of action means that a plan is not determined or is undecided.

In this context, there are two distinct concepts, one having to do with uncertainties to the factual world, the other having to do with uncertainties of the mind. This duality is to be tackled by geo-technical reliability assessment.
The uncertainty in the subsurface modelling receives great focus because it involves risk and hazard as a major element. According to Farrow (2003), the uncertainty or risk is nothing but a measure of the difference between estimation and reality. In geostatistics this corresponds to the concept of estimation error. On a basis of a variogram it is possible to calculate, in advance, the variance of this error, called the kriging variance. In this case the estimation variance on the property is the issue of concern that such a problem can be solved by means of geostatistics in the case of regular sampling.

However, the assumption of applying estimation error as uncertainty measurement is based on the fact that, the known samples fall in the linear normal distribution. In reality, it rarely occurs in that way, especially in the situation of the complicated sedimentary environment.

As explained by Zou et al (1993), Uncertainty, complexity, and dynamism have provided continuing challenges to man’s understanding and controlling of his physical environment.

### 2.4.1 Factors for reliability of models

Diverse sources of uncertainty are involved in to the final 3D subsurface models. Bowden (2003), illustrated modelling constraints resulting uncertainty as presented in figure 2-3 and Gorden (2001), indicated possible sources of uncertainty in soil properties modelling processes as shown in Figure 2-4. Most geoscientists do believe that sources of uncertainty are so many but among them the most important and influential parameters are categorized under data quality, and interpretation quality. Modeling algorithm selections and modelling resolution are not well considered for subsurface modelling of lithology and stratigraphy units. The following diagram represents a dense data scenario, (dense or uniformly sampled data) showing that straight joints are a reasonable expectation. This highlights the ability to automate the modelling process.

![Figure 2-2 Showing the dense and sparse data for subsurface geo-object modelling and visualization (Cox, 1997)](image)

Whenever modelling is planned with sufficiently dense data, little interpretation is needed, but the attention should be paid to geological interpretations when the data show an erratic distribution even with a high density of data. Bowden (2003) illustrated modelling constraints resulting uncertainty as shown in Figure 2-3 below:
Uncertainty arises from a number of sources. According to Gordon (2001) the main contributor for the source of uncertainty being the frequency and magnitude of loads, material properties, geometry and the analytical models used in evaluating performance. Gordon mentioned two fundamentally different kinds of uncertainty: Aleatory uncertainty is attributed to natural variability where as Epistemic uncertainty is attributed to a lack of knowledge. Gorden (2001) presents source of uncertainties in soil properties modelling processes as shown in Figure 2-4.

The most important uncertainties are due to the geological model, economic conditions and technological development. According to W. H. Tang (1996), Model uncertainty is often a dominant source of uncertainty in geotechnical reliability evaluation caused by limitations in data quantity and quality. Model uncertainty leads to uncertainty in the failure rate for a design.
The benefits of an integrated system approach to fill the gap or information in the sparse data can’t be taken as guaranteeing system (approach).

Uncertainties exist in both form field data as well as during the interpretation of the data for the modelling process. Field data uncertainty may be introduced by errors in assumed local environmental input and various inputs based on the natural and man-made influences. The uncertainty in the modelling process and interpretation of the data isn’t always quantifiable because, not every fact in geology can be quantified in temporal sense. A constructed subsurface model is a subset of different factors either dynamic or static. Sometimes theory of uniformity may not work such as “Present phenomenon’s are the key to the past”. In situations like the Netherlands where some parts of the western areas are created by people and most of the sub surface deposits are modified or removed for the sake of exploitation of natural resources such as peat, coal, gas and also as a result of civil constructions such as dikes, roads and canals. The influence of the sea on the surrounding geo environment is insignificant for the last century and very minimal contributions to the processes on the surface of the land but intrusion of the sea water into the ground water might give a contribution to the rise in the ground water level. So constructions of the subsurface 3D modelling in this area needs recent data and also note the paleo geomorphology of the region. Model likelihood is also inherent to the modelling process, which provides linkage between the phenomena being measured in the field survey, and physical, chemical and biological properties and processes occurring in the subsurface geo-objects. For any size (type) of project, the minimum cost/ investment in the process will guide the level of the data quality and density. In most of the cases, the common ambition is to have a very good quality data with the minimum amount of resource. In the business world, demand for detailed information and quality result from cheap labour but may not give representative information, especially for the mining industries. Model reliability also influences the critical applications at hazardous sites for the planning of a management system. In general, the reliable geo models built by geo-reasoning system will assist planners and decision makers for the design, implementation and supervision strategies of simple to complex subsurface engineering and mining structures.

The author would like to give one particular example in data collection and organization during the fieldwork. In normal geoscience site investigation or mineral exploration practice, especially large and expensive projects, demand an experienced expert for coordination, supervision and overall management of the job on the site. Senior professionals normally don’t prefer to stay in a routine job, especially, in areas, which require regular follow-up and monitoring. For example, in case of core drilling, in a soft formation for coal exploration, monitoring of core data, in situ measurement, testing, and sampling of coal is very important. Quality of coal in horizontal or vertical directions is not generally uniform, so for laboratory analysis, experienced professionals must collect samples at regular intervals based on existing geological conditions. In the remote parts where facilities are poor and health threatening insects and animals exist, even the junior professionals don’t like to be present during the night by staying behind the boring rig. Then the major routine boring activity, controlling, handling and sampling will be handed over to the man in charge of operating the drilling rig. There is no mathematical rule, which can define the degree of uncertainty of the data collected by the driller or junior professionals. Maybe in case of bored core samples comparison of the data may help but if the material is weak after exposure to open air for half a day or night, this will result in lose of physical properties due to loss of moisture content etc. Imagine the impact of these types of data collected by non-professionals will result in the final modelling processes. So the effect of uncertainty
process involves three distinct groups, (a) Geo Scientists (b) Integrated assessment modellers (c) Decision-makers (Planners, politicians and their representatives in negotiations), stakeholders and the public.

2.4.2 Bases for quality interpretation

In general, the source data to be considered for the subsurface modelling may be either from hard or soft material and or both. Regardless of the sources of the data, the amount of data available, and its level of quality, the subsurface characterization should consider the most important parameters in the interpretation processes, consisting of geo knowledge of the interpreter, the scale of investigation and the purpose of the modelling.

2.4.2.1 Geo-knowledge

Assuming the quality of data used being good enough, the interpretation quality seems to be based on the judgment of the interpreter with geological knowledge of local and or general geological background of the area or similar geological environment. Considering that, the soil or rock units vary rapidly within very short distances, it becomes difficult to reflect the realistic litho facies distributions in the interpretation.

Hack (2003) has described the real situation observable in the Netherlands, especially the western part of the Netherlands where sedimentary layers have mostly a marine or a fluvial origin. Assume that a foundation has to be made on a sand body in the sub-surface. Some boreholes CPT's (Dutch Cone Penetration Tests), have been made and show in all a sand layer to exist roughly at the required depth. Now the interpretation starts. If the sand layer is of marine origin it can reasonably safely be assumed that the layer is continuous, however, if the sand layer is of fluvial origin it is in contrary likely to be a lens with a limited lateral extension, and may or may not be continuous between two boreholes or CPT's. An engineer who knows in which formation he is working the correct interpretation will result, while, his colleague who does not know or who makes the wrong assumption, produces a completely wrong interpretation with all consequences for the foundation and the building resting on it. So no decent analyses of hazard and risk can be made if these two interpretation errors cannot be quantified.

2.4.2.2 Scale of investigation

The principle of homogeneity and isotropy of geo-objects is a subjective phrase and a relative approach to simplify natural phenomena such as rock/soil units as exist in a real world. Let us consider a homogeneous outcrop of rock/soil which seems to be isotropic in a dimension of 1m³. In theory, we can say homogeneous, isotropic, continuum etc. In real situation, if we conduct very detailed investigations at a level of mm, it is almost impossible to find homogeneous and isotropic earth material, this means there is a minimum degree of certainty to encounter a completely homogeneous geo-object in real world. For civil engineering practice the expression relatively stable or susceptible to processes of deformation will frequently be used with implication of risk or failure of slope, safety factor calculations provide a certain value, but the influence of this small or micro scale variability of internal or external constituents and characteristics of geo-objects are not yet considered in modelling. The smaller the area to be investigated, with relatively a great detailed information into the modelling, the higher the likelihood of
the model to represent the real world. The reliability of the model is more promising when the numbers of representative data incorporated from different disciplines are in agreement with each other.

According to Hack (2003), the allowable variation of the properties within one geo-technical unit depends on: 1) the degree of variability of the properties within a mass, and 2) the context in which the geo-technical unit is used. A groundmass containing a large variation of properties over a small distance necessarily results in geo-technical units containing larger variations in properties. This is because it is impossible to establish with sufficient accuracy all boundaries among the various areas with different properties within the mass. The smaller the allowed variability of the properties in a geo-technical unit the more accurate the geo-technical calculations can be. Smaller variability of the properties of the geo-technical units involves, however, collecting more data and is thus more costly. The higher accuracy obtained for a calculation based on more data has, therefore, to be balanced against the economic and environmental value of the engineering structure to be built and the possible risks for the engineering structure, environment, or human life. The variations allowed within a geo-technical unit for the foundation of a highly sensitive engineering structure (for example, a nuclear power station) will be smaller than for a geo-technical unit in a calculation for the foundation of a standard house.

The reliability of subsurface models is judged and governed not only by the type, quality and quantity of the data used to build the model but also the reliability of interpretation and judgments given on the actual natural situation.

2.4.2.3 Need for the reliable $G^2$ model

Sub-surface application projects involves in uncertainty of the models. Hence the risk and forecasting probability of hazard depends on the reliability of the model but the quality of model depends on the cost of investment, purpose of project and time required for an assessment.

According to Rosenbaum (2003), based on the applied field and the modelling depth, subsurface geological modelling can be classified into two:

- Shallow subsurface modelling involves characterization and precise definition of civil and geo-technical engineering and environmental application. In urban areas where many infrastructures and utility elements are located requires high feature resolution, precise property matching and the ability to differentiate conditions in a noisy environment.
- Deep subsurface characterization for ground water resource evaluation, environmental contamination assessment, under ground storage facilities and petroleum exploration.

According to Kelk, (1991), the industry requires a system for interactive creation of spatial and spatio-temporal models of the physical nature of portions of the earth’s crust. The capability to be effectively modelled and visualized:

- Geometry of rock- and time-stratigraphic units (superposition)
- Spatial and temporal relationships between geo-objects (chronology)
- Variation in internal composition of geo-objects (genesis)
• Displacements or distortions by tectonic forces (discontinuity)
• Fluid flow through rock units (permeability)

2.5 Conclusion

• Digital 3D subsurface models are important and useful in fields of mining industry and geo-technical engineering, in addition, modification is possible to manage and update the created model whenever additional data are available. However, the level of reliability of models depends on the type of project, and time of data acquisition.

• Three-dimensional geological modelling has been used in the fields of mining industry, reservoir engineering, civil engineering projects and associated environmental hazards.

• The level of uncertainty depends on different factors. However geological modelling in a sedimentary basin of horizontally bedded and undisturbed conditions with limited amount of subsurface information may be possible a model with reasonable degree of reliability can be constructed.

• Different modelling approaches are available for subsurface modelling but the judgment for verification of the generation of a model depends on geological knowledge of the modeller.

• The uncertainty exists in the modelling process and the reliability level of models is based on the objective of the study and type of modelling processes used.

• The smaller the allowed variability of the properties in a geo-technical unit the more accurately the geo-technical model can be produced.

• In general the reliability of sub surface geo-model is judged based on the complexity of the site, acceptable quantity of data and quality of information used for interpretations.

2.6 Discussion

• Nowadays, the likelihood of the geological and geo-technical models is a point of discussion among geoscientists as well as decision makers and many researchers. Geology varies from place to place based on factors as depositional history, diagenesis, tectonics, endomorphic and exo-morphic processes. However geometric complications and irregularities in properties of the geo object, invite the professional for inter-
interpretive approach than quantification or observation. In some cases due to the fact that migratory behaviour of some geo-objects, the model to be constructed could depend on time.

- Geometric complications of geo-objects are commonly observed as being due to dynamic processes, which result in either building up or modifying (changing) the internal and external surfaces of the earth. Cycles of tectonics and related phenomena are responsible for the creation of faulting, folding, shearing processes, which might bring together formations of different age and origin. To interpret the geometries resulting from this complication will be very difficult.

- The process of sedimentary deposition and sudden change in the water current velocity and source of material results in the variability of layers with irregularities of structural boundaries such as depositional laminations and lateral facies changes. In general, within the geological units, especially, at variable depths as a result of overburden pressure and temperature the materials spatial variability of showing properties, there are degree of consolidation, porosity, density, cohesion, strength, elasticity and mineralogy exists.

- The main source of misunderstanding among geoscientists on the constructed model is due to variability in the registration of the data on an existing standard format or lacking of standardized format of the data sets used in geoscience modelling. In any case there is a certain amount of uncertainty incorporated into any model from either the data set itself or from knowledge of the modelling processes. So the result of subsurface model should not be regarded as a photocopy of the Geo-object.
3 Research Methodology

3.1 Introduction

It is becoming increasingly clear that achieving a more complete understanding of subsurface geo-
objects will require ever-increasing degrees of integrating available sparse data. The availability of mu-
li discipline geo-data is rare due to the consideration of investment cost. So the question comes, i.e.,
how far a reliable subsurface model can be constructed based on limited data.

Though different methods exist and many researchers applied different methods to build 3D subsur-
face geological and or geo-technical models for different geo-scientific fields, the method to evaluate
and assess the likelihood of models still is largely unknown. In this study, the integration of a geo-
knowledge reasoning framework into current 3D modelling systems is conducted for generating mul-
tiple models; the conceptual semantic likelihood assessment approach is proposed to rank the con-
structed models (Chapter 7).

3.2 Methodology

The adopted research methodology is illustrated as shown in Figure 3-1.Steps for conducting the mod-
elling and model likelihood assessment are as follows:

- Analysis and integration of the multi-sources data.
- Information extraction from the collected available data.
- Extraction of geo-knowledge from data/information and implementation of a geological rea-
soning framework for geological and geotechnical interpretation.
- Constructing multi-models based on various interpretations by applying volumetric modelling
approaches and property modelling methods.
- Validation process by omitting 10% of known data before the modelling process and compari-
son of the constructed models.
- Assessment of the likelihood of the models by executing a semantic likelihood index approach

In most of 3D modelling approaches and model validation methods, the geo-knowledge is rarely in-
corporated into the 3D modelling system as well as in the model assessment process. Although some
model assessment methods are available; the interpretation quality remains mostly unknown. Accord-
ing to Hack (2003), the establishment of geo-technical units, as well as the boundaries and the allowed
variation of properties within each unit, depends on engineering judgment. It requires, therefore, the
integration of a geo-knowledge reasoning system into a 3D modelling system to construct multiple
geological and geotechnical models. Then the decision can be made to choose which of the models
best fits the specific application given.
Figure 3-1 Framework of assessing likelihood of geo-models (Geo-modelling workflow scheme)

3.3 Interpretation Quality Control

Given the data available, there are many factors influencing the interpretation process and the setup of the conceptual geo-object model design. According to TNO-NITG (2000), the knowledge acquisition as well as geo-intelligence from the known data and information is in the decision-making. The decision making process from the data stage is illustrated in Figure 3-2. As defined by TNO-NITG (2000), data is the symbol, which is not interpreted yet; information is something with a meaning, and knowledge means the ability to assess the meaning.
The interpretation of the lithology and geology from a known data set is normally done on the basis of the local geological environment, spatial distribution of the units, and geological process. According to Keefer (2002), the modelling objectives need to address at least the following to be able to assess the quality of a model:

- stratigraphy and complexity of the geologic system,
- spatial distribution of the data,
- data quality and quantity,
- area or volume to be modelled,
- sizes and shapes of anticipated surface features, selections based on the complexity of the geologic deposits, the extent and location of data clusters, the variation in data spacing within these clusters, and the intended applications of the model.

In this thesis, I adopt or summarize the fundamental conditions in geo-knowledge acquisition, which in turn can be used for constructing geological and geo-technical models (FCCG2 M).

It can be expressed as semantic function of the following parameters:

\[ FCCG^2 M = f (OS, GE, GM, UA, ST, SD, TF, PG); \]  

In which the different parameters are describing features as follows:

**OS:** Objective of the work and scale of investigation, which depends on, for example,
- Multi purpose (data gathered for the assessment of natural resources planning, for the sustainable development strategies, etc.)
- Demand driven (data collected for specific problem, investigation, or exploration; either, before or after the actual event).
**GE:** Geological Environment, which incorporates features such as:
- Genesis of deposition (depositional environment such as marine, fluvial, lacustrine, continental, etc)
- Types of deposits (the name of deposit, formation, soil, etc)
- Processes involved (transportation and depositional agents such as water, gravity, wind etc)
- Overview of the deposition history (regression or transgression of the sea or both, overflow of rivers etc)

**GM:** Major Geological/Geo-technical units /soil units, which depends on, for example:
- Types (marine sediment, fluvial and or lacustrine, sand, clay, peat etc)
- Intra relationship (the boundary nature locally and/or regionally, inter fingering or sharp, crossing, undulating, uniformly layered or abrupt change in sequences etc)

**UA:** Unit Association depends, for example, on:
- Plant remains (type of plant remains, and its position and nature of its distribution vertically and horizontally indicating its strength and stability etc)
- Animal remains (the presence of animal remains, type and distribution and association such as shell, either marine or fresh water shell etc)
- Foreign components (natural such as detritus rock components, man made artifacts)

**ST:** Extent and types of structures, for example:
- Normal conditions (graded bedding or reverse bedding, banding etc)
- Fault or fold any scale (controlled surfaces, lines or geo-objects)
- Settlement (subsidence), confined to a specific area or region with mono linear and/or multiple etc)

**SD:** Spatial distribution (X, Y, Z),
- Shape, Size and extent of geo-objects of special interest from previous knowledge/work.

**TF:** Time with respect to age and process, which incorporates factors such as:
- Construction life, (any disaster information recorded or historical, active or dormant and its rate with respect to the time before and/ or after the area has been used for a development plan)
- Geological time, (relative and absolute age of the geo-object under investigation with respect to the confining or surrounding geology etc)
- Human interferences and (the rate and intensity of human interference with the natural object which can influence surface or subsurface water level etc)
- Hydro-geological processes observable as spatial features such as the influence of marine water intrusions to the surrounding area with an increase in the ground water table, and/or the contribution of surface water etc)

**PG:** paleo-geomorphological framework
- Position and location of natural and manmade drainage lines, etc.

All of these parameters are required and are to be considered to build the conceptual model of the modelled geo-object.
3.4 Methods for evaluating reliability (validation of models)

Evaluation of the reliability of the generated models is of great concern. Of any object above the ground having direct access dimensions can be measured and quantified since it is transparent, however for subsurface geo-objects it is unlikely to have a direct contact and validation is normally subjective, time consuming and expensive. The possible methods of approach for evaluating reliability of built multi models are discussed as follows:

3.4.1 Comparison with the real world

Comparisons of the constructed multi-model with a present excavation or with something such as production data is the best option but the problem is that this may not be available always because the excavation or mining data may not exist before the modelling process starts.

3.4.2 Multi scenarios approach

Another option is building multi models of the same area by different professionals (i.e., different interpretation knowledge), which is a two-step procedure. Validating the model with additional information. For example 10% of available data will be kept for validation of the model. The model with a high correlation of the reference data will represent a reliable model.

3.4.3 Expert knowledge based

If detailed information is absent, there is no possibility of validating the model; in this case, the model is built based on prior knowledge of an expert. In this case, there is high probability of doubt based on the expert knowledge doing the modelling process; especially in geological environments with high variability of units over short distance and the thinner geo-objects involved for modelling processes.
4 Case Study: Reeuwijk Road project

4.1 Location of the study area

The study area is located in the central western part of the Netherlands. The geographic coordinates in UTM are 114000 to 116000E and 452000 to 454000N covering an area of 3.2 km². 63 bore hole data were considered for 3D subsurface modelling. Reeuwijk with a population of 12,904 is a township in the province of South Holland. The municipality covers an area of 50.10 km² of which 12.21 km² is water.

Figure 4-1 Location map of the test area, 2D/3D position of the boreholes

4.2 Geology in the Reeuwijk area

The geology information is gathered from previous works of different researchers who worked in the test area, from regional studies, and from the geological history of the Netherlands.
4.2.1 Regional geology

The area is mainly dominated by Quaternary geology, i.e., Holocene and Pleistocene formation. Holocene deposits are located in a peri-marine facies. According to Bosch (1994), an important controlling factor for the Holocene geology process is the rising of the sea level, which occurred due to the melting of the continental ice. A second main factor is the isostatic rebound of this northwest Europe part of the crust after Pleistocene loading of Scandinavian icecap and subsequent tilt after unloading with resulting depressions of the Netherlands. During the Holocene epoch, the sedimentation in the area of Gorkum (Map sheet: Gorkum 38 west) is almost completely controlled by the Rhine and Maas rivers. The marine influence is notable in the estuary of Rhine and Maas. Intercalated peat between the clastic rivers sediments (sand in the stream belt and mainly clay in the back swamps) occurs, which was formed in shallow lakes and marshes. The marine deposits are formed in a tidal flat depositional environment comprising of very silty and moderately silty, massive clays coarsening upward (Bosh et al 1994).

According to Gerritsen, (2001), climatic changes after the Pleistocene epoch caused a sea level rise accompanied by a rise of regional ground water table. Sedimentation in Holocene epoch started with the formation of peat (basal peat). A continuous sea level rise caused flooding, as a result medium to fine sand alternated with clay layers, the formation of Gorkum member was deposited in the vicinity of Rhine and Maas. Following the regression of the sea, the thick peat layer, Holland peat was deposited. Peat areas were flooded and covered by Tiel deposits. In the later stage, on top of the Tiel deposits, the anthropogenic soil is covered locally.

Figure 4-2 shows the geological map of Reeuwijk area (After Bosch and Kok 1994), for further information is referred to the original literature.

The description of the lithology units of Holocene deposits indicated in the legend are summarized as follows:

D0g: Tiel deposits characterized by channel deposits locally covered by levee deposits.
D0k.: Tiel deposits characterized by flood plain deposits on channel deposits.
F0k: Tiel deposits characterized by flood plain deposits overlying Holland peat. Shown in the map as.
F3k: Tiel deposits characterized by an alternation of Holland peat and Gorkum deposits (flood-plain and levee deposits).
G0: Holland peat.
4.2.2 Paleo geomorphology

According to Mulder, (1990), half of The Netherlands was covered by ice, during the Saalian glaciations (200,000 years BP). In the central and eastern parts of the country, alluvial deposits were pushed by the ice to form ridges and hills. These ridges and hills were left behind when the inland ice retreated.

Later, a coastal barrier system began to develop in the present coastal area in the Holocene epoch. Protected from the sea by these barriers, large back swamps could develop. Later during the Holocene sand dune barriers formed along the western coastal zone. Thus, three major geomorphologic features existed: the sand dunes, the ice-pushed ridges, and a depositional basin lying between the former two. The basin had ideal conditions for the development of peat and clay soils since it was subject to flooding either by tidal inflow or by the Rhine River floods leading to marsh and back swamps environment, Mulder, (1990).

At present the Holocene fluvial plains consist of three major landforms: forelands, natural levees and back swamps. The forelands, or outer marshes, lie outside the dikes (winter dikes) and are subject to flooding almost annually. The embanked flood plains inside the dikes can no longer be raised due to silting processes and this process is still continuing in the outer parts of the flood plains (Amurane,
2003). Around 5000BP the coastline reaches the west of the Netherlands in most eastern boundary (Bosch, 1994).

4.2.3 Depositional age and environment

The fluvial sediments, together with clastic marine deposits and intercalated peat layers in the area are all regarded to belong to the Westland Formation (Nomenclature, 2000). Different layer packages are distinguished within the Westland Formation (Zagwijn & Van Staalduinen, ed., 1975):

- Tiel Deposits: clastic sediments deposited in fresh water younger than 3750 BP
- Holland peat: Peat formed in brackish or fresh water condition.
- Gorkum deposits: clastic sediments deposited in fresh water older than 3750 BP.

The subdivision of the clastic sediments of the Westland Formation in fluvial deposits of the Gorkum and Tiel deposits from the Tidal flat and estuary deposits of Calais Duinkerke is based on the quality (salt contents) of the water in the environment during the deposition (Bosch, 1994). The following main parameters were used to differentiate fluvial and marine environments:

- **Fossil:** - the presences of macrofossils, in particular fresh-watershells have been used to distinguish salt and fresh water species.
- **Continuity:** - The presence of continuous layers of fine sand indicates tidal flat conditions but the presence of clay with wood indicates a fresh water environment.
- **Organic component:** - Organic rich clay that belongs to the fresh water environment is brown in colour due to the presence of iron, while salt-water clays have a grey colour in which the iron is bound to sulphides.

4.2.4 Types of alluvial deposits

Based on the sedimentation process, the Holocene fluvial deposits of the area can be divided into the following groups (Bosch et al, 1994)

- **Channel deposits:** sediment deposits formed mainly from the activity of river channels. It comprises channel lag deposits; point bar deposits, channel bar deposits, and channel fill deposits of sand, which sometimes may be gravelly.
- **Bank deposits:** - sediment deposits formed on the riverbanks and are produced during flood periods. They include levee deposits and crevasse splay deposits of sandy clay and clay.
- **Flood basin deposits:** – they are essentially fine-grained sediment deposits formed during heavy floods when river water flows over the levees into the flood basin. They include flood basin deposits and marsh deposits. In Netherlands the Holocene fluvial deposits are named Gorkum and Tiel depending on their correlation to Calais and Dunkirk marine deposits.
- **Natural Levee:** - A long broad low ridge or embankment of sand, silt, or other material, built by a stream on its floodplain and along both banks of its channel during flood stage
when the coarser sediment is deposited as a result of suddenly decreased velocity once spilling over to the floodplain.

4.2.5 Types of peat

The extensive formation of peat took place in the Netherlands during the last 10000 years, i.e., the Holocene epoch. Climatic conditions were temperate, moist and highly favourable for peat accumulation (Van Staalduinen, 1979).

Peat is defined as an unconsolidated deposit of semi carbonised plant remains in a water-saturated environment, such as a bog or fen, and of persistently high moisture content (at least 75 percent). According to Bosch (1994), there are three types of peat in Westland formation in the map sheet area Gorkum west (38W):

Forest peat: - characterized by the presence of many pieces of wood of alder (Alnus) and willow (Salix). Formed in a nutrition rich (eutrophic) fresh water environment.

Reed peat: - mainly composed of the remainders of reed (Phragmites) and sedge (Carex), this was formed in nutrition rich fresh water and locally also in a weakly brackish environment. It also occurs as intercalations in the forest peat.

Sphagnum peat: - mainly made up of the reminders of sphagnum. It was formed in a nutrition poor (oligotrophic) environment, which was supplied by rainwater only. In the map sheet, it is not exposed but the Zuidplas polder (south Lake polder), came in existence as a lake due to the exploitation of this type of peat, Bosch, et al (1994).

According to Staalduinen et al., (1979), a number of cold and warm phases have been established from the paleontological data. The cold phases are called glacial and there are open vegetations but the warm phases are interglacial with forest domains.

4.2.6 Processes of peat formation in Holland

The formation of peat takes place when the environment at the location is so moist and quiet, that a large part of the plant remains after dying is not transported away or decayed, but piles up. Geographic positions commonly favourable for the depositions are:

- Places with shallow water (less than 2m deep) and small sediment supply.
- In the lower reaches of the major rivers, the floodwater becomes stagnant due to the smaller gradient of the Holocene rivers.
- In the standing water of the back swamp areas.
- In the abandoned riverbed of the river system.

4.3 Land settlement problem
The Land settlement problem in Reeuwijk district is a critical concern for the community. The ongoing settlement of the ground surface is estimated to be 1cm per year, according to the personal comments by Rupke (Amurane, 2003). Settlement causes deterioration of road traffic conditions, and as consequence the maintenance work of roads has to be carried out regularly in a rather short space of time. This results in financial problems to the municipal authorities that have to allocate a major part of the community annual income to road maintenance purposes.

4.3.1 Causes for the settlement

Over large parts of the Netherlands, the ground is subsiding as a result of natural, long-term tectonic processes and human activities. The most important man-induced reasons for the subsidence are drainage, groundwater abstraction, and the exploitation of gas, oil and other minerals (e.g. salt and coal). Accompanying the subsidence is a rise (relative and absolute) of the sea level. These phenomena have important long-term impacts on the entire Dutch coastal area and on coast-forming processes particularly on the formation of beaches and dunes as protection against the sea and for the upwelling of salt water further inland. The construction of sea works has clear short-term effects on the coast, accelerating deposition in some places and erosion in others (TNO-NITG, 2003).

The ground settlement in the district of Reeuwijk is partially caused by continuous withdrawal of groundwater that is carried out to allow agricultural and other land use practices in the meadow areas. The geology of the area favours for the occurrences of settlement, in which the alternation of thick layers of clay and peat with sand has the direct relation with the fluctuation of ground water table and the consequence of water withdrawal is the shrinkage of the soil layers either by normal consolidation of clay or oxidation of peat.

4.3.2 Consequences of the problem

The implications of such settlement problems cause short and long-term social and economical effects in the safety aspects as well the continuous subsidence increases the areas in risk of getting flooded. Therefore, the strategies and decisions regarding road maintenance as well as land use practices may not be sufficient to satisfy decision requirements such as:

- Cost reduction
- Increased safety conditions
- Effective decision making
- Ensure quality control
- Wise use of space

4.3.3 Remediation
To plan for remedial measures for this type of settlement problems, both geological and geo-technical models need to be considered before any decision made. A subsurface geological and geo-technical modelling can serve in locating the position of different layers. It has proven that, peat and clay layers to be susceptible to ground settlement in the Netherlands. Knowledge about the position of peat and clay with relation to the sand layer and their thickness as well as spatial continuity is very important for any future planning made.

Assessment of the borehole data from the area indicates that an inconsistency of layers exists. The inconsistency of the marker beds (clay, peat) indicates their deposition is either not in a homogeneous environment or influenced by different depositional processes (genesis). This study proposes and tests a number of steps that could be used within multi modelling approach based on geo knowledge reasoning framework. The result also might facilitate in the characterization of a Decision Support System to assess settlement problems, not only in the study area but also in the region.
5 Geo-knowledge reasoning based 3D Modelling

5.1 Introduction

For an effective use of time, money and space, there is an increasing demand for reliable subsurface models on a very limited data set. The use of a limited data set limits the possibilities to validate the reliability of models. Especially, the use of multi source data collected by different professionals with varying levels of experience, education and expertise, and approach of work, will contribute to this difficulty during an interpretation process. However, to overcome the difficulties, an alternative option is available.

Knowledge is extracted from various data sources done by previous work, and then the subjective reasoning is conducted based on understanding of the geological processes and the modelling objective. Simple engineering projects in complex geological structures and very complicated subsurface engineering structures demand higher levels of expertise and skills, and more experience to construct more reliable models.

In this study, by building a geo-knowledge reasoning framework, different geological interpretations are executed. Hence, multi-volumetric models as well property models (unit weight) are constructed. Then the model comparison and ranking follow in chapter six and seven respectively.

The first part presents the data/information used for the 3D subsurface model construction. The second part contains the discussions on the criteria to build the reasoning framework. The last part discusses the difficulties and limitations in the modelling process.

Rockworks 2002, which is developed by American Rockwork T\textsuperscript{M} Company, integrated software is useful for geological data processing and 3D model construction. It consists of a borehole data manager for the entry of borehole data such as: observed lithology, stratigraphic boundaries, orientation, and location of the hole. It also contains utilities for gridding, contouring, solid modelling and 2D /3D feature analysis.

5.2 Geological data/information used for 3D Modelling

The available data and information for constructing 3D subsurface models includes: Bore hole data (63 holes), geological sections constructed from CPT data, CPT data (5), reports, and relevant literatures. They are described briefly in the coming sections.
5.2.1 Borehole data

In this study, the data used for the subsurface volumetric and property modelling is originally from the NITG-TNO, previously been used in the M.Sc research for ground settlement problem calculation of the Reeuwijk area by Amurane (2003). The distribution of boreholes is not regular, uniform, and the depth of individual holes respective to their elevations show considerable variations. The summary of the borehole data is shown below in table 5-1.

Table 5-1 Statistical summary of 63 bore holes

<table>
<thead>
<tr>
<th>Item</th>
<th>Description</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Total number of holes</td>
<td>63</td>
</tr>
<tr>
<td>2</td>
<td>Maximum depth</td>
<td>9 m</td>
</tr>
<tr>
<td>3</td>
<td>Minimum depth</td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td>X/Easting-Minimum</td>
<td>114400 m</td>
</tr>
<tr>
<td>5</td>
<td>X/Easting _Maximum</td>
<td>115980 m</td>
</tr>
<tr>
<td>6</td>
<td>Y/Northing _Minimum</td>
<td>452010 m</td>
</tr>
<tr>
<td>7</td>
<td>Y/Northing _Maximum</td>
<td>453980 m</td>
</tr>
<tr>
<td>8</td>
<td>Elevation minimum</td>
<td>-1.9 m</td>
</tr>
<tr>
<td>9</td>
<td>Elevation Maximum</td>
<td>-0.9 m</td>
</tr>
<tr>
<td>10</td>
<td>Average depth</td>
<td>6.5 m</td>
</tr>
<tr>
<td>11</td>
<td>Total length of the bored hole</td>
<td>407.44 m</td>
</tr>
<tr>
<td>12</td>
<td>Total area</td>
<td>3.2 km²</td>
</tr>
</tbody>
</table>

5.2.1.1 Data base construction

Before constructing the database and starting the data interpretation, a systematic and complete data validation is conducted for all records to guarantee that no errors exist. The database is built according to the required format used in Rockworks 2002. The database consists of several tables that can be prepared in a spread sheet, i.e., bore hole collar, bore hole survey, lithology, stratigraphy tables, etc. The data from the database is imported in Rockworks 2002. Finally, a data analysis and geological interpretation starts in the 3D modelling system.

5.2.1.2 Borehole location

Location is used to indicate only one record per hole. Each record includes hole identifier; bore number, Eastings, Northings, Elevation and Total Depth as presented in Table 5-2.
5.2.1.3 Survey data

Downhole survey information defines the change in azimuth and dip along the trace of each hole (Table 5-3). In this data set, the boreholes are bored vertically and only two records are given since the hole is too shallow no deviation is recorded along the hole.

Table 5-3 Example of Borehole survey data

<table>
<thead>
<tr>
<th>Hole ID</th>
<th>Bore ID</th>
<th>Depth</th>
<th>Bearing</th>
<th>Inclination</th>
</tr>
</thead>
<tbody>
<tr>
<td>452-114-0005</td>
<td>452-114-0005</td>
<td>0</td>
<td>0</td>
<td>-90</td>
</tr>
<tr>
<td>452-114-0005</td>
<td>452-114-0005</td>
<td>6.41</td>
<td>0</td>
<td>-90</td>
</tr>
<tr>
<td>452-114-0006</td>
<td>452-114-0006</td>
<td>0</td>
<td>0</td>
<td>-90</td>
</tr>
<tr>
<td>452-114-0006</td>
<td>452-114-0006</td>
<td>7.5</td>
<td>0</td>
<td>-90</td>
</tr>
<tr>
<td>452-114-0007</td>
<td>452-114-0007</td>
<td>0</td>
<td>0</td>
<td>-90</td>
</tr>
<tr>
<td>452-114-0007</td>
<td>452-114-0007</td>
<td>6.61</td>
<td>0</td>
<td>-90</td>
</tr>
<tr>
<td>452-114-0008</td>
<td>452-114-0008</td>
<td>0</td>
<td>0</td>
<td>-90</td>
</tr>
<tr>
<td>452-114-0008</td>
<td>452-114-0008</td>
<td>7</td>
<td>0</td>
<td>-90</td>
</tr>
</tbody>
</table>

Notes: Hole ID: Primary key of hole, Depth: depth range survey conducted in meter, Azimuth: direction of inclination/bearing of the borehole, Dip: Amount of Inclination/deviation

5.2.1.4 Lithological data table

Lithological table stores, the borehole data set of the sampled lithology (soil units) with the interval of depth as shown in Table 5-4.
Table 5-4 Examples of Bore hole Lithology data

<table>
<thead>
<tr>
<th>Hole ID</th>
<th>Bore number</th>
<th>Depth-1</th>
<th>Depth-2</th>
<th>Lithology</th>
</tr>
</thead>
<tbody>
<tr>
<td>452-114-0005</td>
<td>452-114-0005</td>
<td>0</td>
<td>0.4</td>
<td>K</td>
</tr>
<tr>
<td>452-114-0005</td>
<td>452-114-0005</td>
<td>0.4</td>
<td>2.6</td>
<td>V</td>
</tr>
<tr>
<td>452-114-0005</td>
<td>452-114-0005</td>
<td>2.6</td>
<td>3</td>
<td>K</td>
</tr>
<tr>
<td>452-114-0005</td>
<td>452-114-0005</td>
<td>3</td>
<td>3.5</td>
<td>V</td>
</tr>
<tr>
<td>452-114-0005</td>
<td>452-114-0005</td>
<td>3.5</td>
<td>4</td>
<td>K</td>
</tr>
<tr>
<td>452-114-0005</td>
<td>452-114-0005</td>
<td>4</td>
<td>4.2</td>
<td>K</td>
</tr>
<tr>
<td>452-114-0005</td>
<td>452-114-0005</td>
<td>4.2</td>
<td>4.5</td>
<td>V</td>
</tr>
<tr>
<td>452-114-0005</td>
<td>452-114-0005</td>
<td>4.5</td>
<td>5</td>
<td>K</td>
</tr>
<tr>
<td>452-114-0005</td>
<td>452-114-0005</td>
<td>5</td>
<td>5.4</td>
<td>V</td>
</tr>
<tr>
<td>452-114-0005</td>
<td>452-114-0005</td>
<td>5.4</td>
<td>5.6</td>
<td>V</td>
</tr>
<tr>
<td>452-114-0005</td>
<td>452-114-0005</td>
<td>5.6</td>
<td>6</td>
<td>V</td>
</tr>
<tr>
<td>452-114-0005</td>
<td>452-114-0005</td>
<td>6</td>
<td>6.2</td>
<td>V</td>
</tr>
<tr>
<td>452-114-0005</td>
<td>452-114-0005</td>
<td>6.2</td>
<td>6.4</td>
<td>V</td>
</tr>
<tr>
<td>452-114-0005</td>
<td>452-114-0005</td>
<td>6.4</td>
<td>6.41</td>
<td>Z</td>
</tr>
</tbody>
</table>

Notes: Hole ID: Primary key of hole, Depth to Top: top elevation of individual soil layers, in meter indicated as Depth –1, Depth to base: bottom elevation of individual soil layers, in meter indicated as Depth-2, Lithology: Soil type: K = clay (klei), V = peat (veen), Z = sand (zand)

5.2.1.5 Stratigraphic data table

The stratigraphic table stores the interpreted stratigraphic information from the data above. The interpreted stratigraphy is entered into the stratigraphic table, with depth to top and base of formation. The interpreted stratigraphic formation is set in the order of chronology, i.e., the youngest unit on top, the oldest one at the bottom.

Table 5-5 Example of Down hole interpreted stratigraphy data

<table>
<thead>
<tr>
<th>Hole ID</th>
<th>Bore number</th>
<th>Depth-1</th>
<th>Depth-2</th>
<th>Formation</th>
</tr>
</thead>
<tbody>
<tr>
<td>452-114-0005</td>
<td>452-114-0005</td>
<td>0</td>
<td>0.4</td>
<td>Tiel Deposits</td>
</tr>
<tr>
<td>452-114-0005</td>
<td>452-114-0005</td>
<td>0.4</td>
<td>3.5</td>
<td>Holland peat</td>
</tr>
<tr>
<td>452-114-0005</td>
<td>452-114-0005</td>
<td>3.5</td>
<td>5</td>
<td>Gorkum Deposits</td>
</tr>
<tr>
<td>452-114-0005</td>
<td>452-114-0005</td>
<td>5</td>
<td>6.4</td>
<td>Basal peat</td>
</tr>
<tr>
<td>452-114-0005</td>
<td>452-114-0005</td>
<td>6.4</td>
<td>6.41</td>
<td>Twente formation</td>
</tr>
<tr>
<td>452-114-0006</td>
<td>452-114-0006</td>
<td>0</td>
<td>0.5</td>
<td>Tiel Deposits</td>
</tr>
<tr>
<td>452-114-0006</td>
<td>452-114-0006</td>
<td>0.5</td>
<td>4</td>
<td>Holland peat</td>
</tr>
<tr>
<td>452-114-0006</td>
<td>452-114-0006</td>
<td>4</td>
<td>4.9</td>
<td>Gorkum Deposits</td>
</tr>
<tr>
<td>452-114-0006</td>
<td>452-114-0006</td>
<td>4.9</td>
<td>7.2</td>
<td>Basal peat</td>
</tr>
<tr>
<td>452-114-0006</td>
<td>452-114-0006</td>
<td>7.2</td>
<td>7.5</td>
<td>Twente formation</td>
</tr>
</tbody>
</table>

5.2.1.6 Depth and elevation distribution of the boreholes

The borehole data in the test area are characterized by variable depth and elevation as shown in Figure 5.1A & B. As the total depth and elevation from histogram frequencies show that, depth of boreholes
ranges from 3 to 9 m, and about 1/3 of the boreholes is bored down to a depth of 7 m below surface. In case of collar position, 1/3 of the holes are located at –1.75 m NAP (National Mean Sea-level Reference).

During the reconstruction of the solid modelling of the lithology as well as the stratigraphy, the variation in the total depth and the elevation of the holes creates some gaps. Therefore, some of the grid cells will not show any category (label) and is recognized as undefined object in the volume calculations for each unit.

![Graphs showing depth and elevation distributions of boreholes]

**Figure 5-1 Indicating frequency distribution of depth and elevation of boreholes**

**5.2.2 Geological and Geo-technical cross-sections**

Many investigators have conducted their research on the lithostratigraphic and chronological set up of the surface geology based on different data sources. In this study, previous geological and geotechnical works are used as sources of information to conceptualise the subsurface conditions of the area.

5.2.2.1 Geology cross section

Part of the regional geological sections (H-H') in map sheet Gorinchem, 38 West, Figure 5-2 shows, that, Tiel deposits are exposed throughout the entire area covering the top part of the section with a thickness of around 1 m. The underlying Holland peat forms also a horizontal layer but in the section, it is designated as Hvb and Hva indicating varieties in origin of its formations. According to Zigterman (2003), the top part is from a forest and the bottom part is from marshy environment.

The underlying Gorkum deposits occur within the Holland peat forming patches of continuous layers. In general, the Gorkum deposit forms undulating surfaces, which might be indicating the absence of a quiet environment during its depositions. The Twente formation forms the bottom part of the section, and is considered as Pleistocene formation. It is not widely encountered because down hole section exposed only 10 m depths from the surface.
5.2.2.2 Geotechnical sections

The geological section shown in Figure 5-3 has been constructed based on CPT data, and originally from NITG-TNO used by Amurane 2003. The section indicates different formations with their assumed chronological order representing the test area (Reeuwijk). Gorkum deposit is engulfed the peat layers which are generally separated in the upper (Holland peat) and lower units (Basal peat).

Figure 5-3 Constructed geological cross-section, part of the Reeuwijk, based on CPT data.

5.2.2.3 Lithostratigraphic sequences

Litho-stratigraphic subdivisions of units in the study area as well as in the surrounding of the study area are summarized in Table 5-6 and 5-7.
Table 5-6 Lithostratigraphic sequences of units at the vicinity of test area (Bosh 1994)

<table>
<thead>
<tr>
<th>Legend</th>
<th>Symbol</th>
<th>Lithology</th>
<th>Stratigraphy</th>
<th>Formation</th>
<th>Environment</th>
<th>Chronology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Qa</td>
<td>Qa</td>
<td>Mainly clay</td>
<td>Anthropogenic ground</td>
<td>Manmade</td>
<td>Artificial</td>
<td>Holocene</td>
</tr>
<tr>
<td>Qb</td>
<td>Qb</td>
<td>Mainly sand</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>Organic clay</td>
<td>Tiel Deposits</td>
<td></td>
<td>West Land</td>
<td>Fluvial</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>Organic clay or clay With remains of peat</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12-14</td>
<td>Sandy clay to clayey sand</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>Sand</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Peat</td>
<td>Holland peat</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>Mixture of clays</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>Clay with plant remains</td>
<td>Gorkum deposits</td>
<td></td>
<td>Peri marine, fluvial (Staffhorst)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>16-18</td>
<td>Sandy clay to clayey sand, locally with plant remains</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Peat</td>
<td>Basal peat</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>Fine to medium sand</td>
<td>Twente fm</td>
<td>Marine</td>
<td></td>
<td></td>
<td>Pleistocene</td>
</tr>
</tbody>
</table>
Table 5-7 Lithostratigraphic subdivisions according to different authors

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Holocene</td>
<td>Duinkerke Deposits</td>
<td>Ijssemeer Deposits</td>
<td>Geulderkafzettingen</td>
<td>Tiel Deposits (Channel deposits: Sand, sandy clay, flood basin clay)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Geulderkafzettingen</td>
<td></td>
<td>Geulafzettingen</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Almere Deposits</td>
<td></td>
<td>Oeverafzettingen</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Flevomeer Deposits</td>
<td></td>
<td>Komafzettingen</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Holocene</td>
<td>Westland Formation</td>
<td>Holland Peat</td>
<td>Holland Peat</td>
<td>Holland Peat (Wood and Phragmites peats)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Calais Deposits</td>
<td>Older Tidal Deposits</td>
<td>Gorkum Deposits</td>
<td>Gorkum Deposits (Channel: Sandy clay, clayey sand, sand, clay)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pleistocene</td>
<td>Twente Formation</td>
<td>Twente Formation</td>
<td>Twente Formation (Cover sands)</td>
<td>Basal Peat</td>
<td></td>
</tr>
</tbody>
</table>

5.3 Geo-knowledge based reasoning framework

In the geosciences field, the principal target of modelling 3D is to locate, define, and identify the type, and shape of geo-objects, and its lateral and vertical extensions in the subsurface. Different approaches can be used to understand about covered geo materials.

5.3.1 Modelling criteria

Before implementing the subsurface modelling process, a conceptual understanding of the site in 3D view and tailoring of an interpretation to available information have been made. As a result, classifications of the lithology and stratigraphic units into different classes are accomplished based on assumed different scenarios (objectives). For example, prior to plot a particular horizon, decisions have to be made as to which layers among individual boreholes actually make up that horizon. The interpretation has been examined and the link or grouping of individual layers among the boreholes to define a horizon /formation has been decided.
5.3.2 Geo-knowledge reasoning Framework built up

A framework is required to transfer components of any developed geological theory to a data model. Such a framework involves the transformation from concepts as developed in the human mind to a conceptual data model and ultimately to a data structure that can be implemented on a computer system (Peuquet, 1984).

Based on a detailed analysis of the current geo-data of the area as well the regional geological history, a geo-knowledge reasoning framework is built as shown in Figure 5-4. The result of the geo-reasoning information can be transferred from the real world to the knowledge representation. In the process of constructing this framework, the most important data information used includes: down hole lithology information obtained from the TNO_NITG comprising of hole identity, location, orientation, depth and description of each unit. The original description records are in Dutch (some example in Appendix I), but some parts have been translated into English by Zigterman (2003).

Important data / information used for constructing a geo-reasoning framework are as follows:
- Down hole information (Hole logs, including the lithology descriptions)
- Local geology (Reports, cross section, maps)
- Regional geology (Reports, cross section, maps)
- Regional stratigraphic sequences (chrono stratigraphic columns and sections)
- Geomorphologic, Hydrogeology and geographic information

Different parameters were considered to interpret the Holocene and Pleistocene sediments of the Reeuwijk area as presented in Figure 5-4. For example, by considering the modelling objective, for site investigation, the procedure to be followed to model the Pleistocene sand: The environment of deposition could be marine, lacustrine or fluvial. Sand occurs either as a continuous layer if originated from a marine environment or discontinuous layers (patches) of sand if originated either from a lacustrine or fluvial environment. It may in general be expected that lenses originating from a fluvial environment would be laterally smaller than those originating from a lacustrine environment The geotechnical property (unit weight) for both Holocene and Pleistocene sand is nearly the same. Note that, the depth and down hole lithology in normal stratigraphic sequences are also assisting an interpretation. For instance, in the Reeuwijk area the Pleistocene sand is underlying basal peat. Such sequences are recognized from the results of previous researchers report and sections (Figure 5-3).
5.3.3 Litho solid model

5.3.3.1 Lithological units modelled

The sediments of the test area, can be subdivided into two three major litho units based on known data:
Clay (k): clay forms the top unit in the entire area originated both by the natural process from fluvial as well as marine and also at places anthropogenic origin wherever a dike is present. Detailed information about the genesis of clay and other sediments are mentioned in chapter 4.
Peat (V): two types of peats can be recognized on the log, the upper (Wood peat) and the lower (basal peat or phragmtis) is encountered in almost 90% of the boreholes. According to Bosch et al, 1994, the basal peat is defined as the oldest Holocene peat layer overlying the Pleistocene deposits. A characteristic for the map sheet Gorkum 38 West is the presence of a thick package of forest peat on top of the deposits of Gorkum.
Sand (Z): sand layers are encountered as Gorkum channel deposits above the peat layer in the Holocene and below the basal peat as Pleistocene sand. The lithology unit distribution used for solid model shows different units of variable size and shape as can be seen in different perspective views. The spatial variation of units in vertical and lateral position shows that patches of units exist in between the major layers. These form discontinuous patches, which could be a result of fluvial deposition (buried channel) or later dissected crossing channel directions by running erosion.

Though, three major units are described and organized separately, in the detailed descriptions of the log, an association of one with the other or mixture of soil units exists such as silty clay, sand clay or clayey sand and so on. Detailed information about the original description of the down hole units is attached in Appendix I

5.3.3.2 Lithology solid modelling

There is only one available modelling approach in Rock works 2002 to create solid litho models, i.e., Randomize blending Algorithm.

In the "Randomize Blending" option, the maximum search radius around the boreholes will vary by depth and there are no abrupt changes of the litho-unit boundary in the resultant model, which looks like a geologist might draw by hand.

Figure 5-5 presents three solid litho models using Horizontal Blending Algorithm but with different modelling resolutions. The subdivision of modelling resolution into three classes (A, B, & C) is presented in table 5-9. As the modelling resolution, grows more refined, the more details information of litho units is revealed. For example, the clay unit is shown in the circle as a reference layer to see the sensitivity of smaller (thin) layers to modelling resolution. Keeping modelling parameters and vertical exaggerations unchanged, more information has been visualized in 100C.

![Figure 5-5 Solid Lithological model with different grid sizes: 100A, 100B & 100C](image)

5.3.4 Solid geological models
Construction of different solid geological models has been made on the basis of the different interpretations, modelling algorithms, grid sizes and data size. The results of the classification with its respective steps of models and comparison has presented in different sections. For the geological modelling, the possibility of different scenarios and uses of multi-model for different purposes was assumed. For example, if a specific layer is studied, a volumetric or property model or both models can be made. In this work both conditions are used and the results are compared with existing sections (Figure 5-2, and Figure 5-3).

The interpretations are based on the conceptual geo knowledge reasoning as mentioned below in Table 5-8. From Model 1 to Model 4, it reflects increased complexity and specific information from the very simple, general situation to complicated. The respective geological models are described and factors affecting models such as grid cell size, modelling algorithms and data size are discussed. Multi geological models built on the different interpretation scenarios and principles are presented in Table 5-8.

Table 5-8 Subdivision of four types of models and associated litho unit

<table>
<thead>
<tr>
<th>Mode</th>
<th>Time</th>
<th>Unit/Formation</th>
<th>Litho Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Holocene</td>
<td>Westland Formation</td>
<td>Clay, sandy clay to clayey sand and peat</td>
</tr>
<tr>
<td></td>
<td>Pleistocene</td>
<td>Twente Formation</td>
<td>Fine to medium sand</td>
</tr>
<tr>
<td>2</td>
<td>UHolocene</td>
<td>Tiel Deposits</td>
<td>Organic clay, sandy clay to clayey sand and sand</td>
</tr>
<tr>
<td></td>
<td>LHolocene</td>
<td>Holland peat, Gorkum Deposits, and Basal peat</td>
<td>Peat, mixture of clay, sandy clay to clayey sand locally with plant remains</td>
</tr>
<tr>
<td></td>
<td>Pleistocene</td>
<td>Twente formation</td>
<td>Fine to medium sand (Cover sand)</td>
</tr>
<tr>
<td>3</td>
<td>UHolocene</td>
<td>Tiel Deposits</td>
<td>Organic clay, sandy clay to clayey sand and sand</td>
</tr>
<tr>
<td></td>
<td>MHolocene</td>
<td>Holland peat</td>
<td>Upper peat</td>
</tr>
<tr>
<td></td>
<td>LHolocene</td>
<td>Basal peat and Gorkum Deposits</td>
<td>Lower peat and clay with remains of plant, sandy clay to clayey sand</td>
</tr>
<tr>
<td></td>
<td>Pleistocene Deposits</td>
<td>Twente formation</td>
<td>Fine to medium sand (Coversand)</td>
</tr>
<tr>
<td>4</td>
<td>Tiel Deposits</td>
<td>Tiel Deposits</td>
<td>Organic clay, sandy clay to clayey sand and sand</td>
</tr>
<tr>
<td></td>
<td>Holland peat</td>
<td>Holland peat</td>
<td>Upper peat (wood peat)</td>
</tr>
<tr>
<td></td>
<td>Gorkum Deposits</td>
<td>Gorkum Deposits</td>
<td>Clay with remains of plant, sandy clay to clayey sand</td>
</tr>
<tr>
<td></td>
<td>Basal peat</td>
<td>Basal peat</td>
<td>Lower peat (phragmites peat)</td>
</tr>
<tr>
<td></td>
<td>Twente formation</td>
<td>Twente deposits</td>
<td>Fine to medium sand/Eolian deposits, (Cover sand)</td>
</tr>
</tbody>
</table>

Visualization of the subsurface information is a very important application of 3D modelling for planning sustainable development. In this study, four different models of chrono-stratigraphic units are presented in Figure 5-6 indicating different possible scenarios of a study area. Common spatial and
topological boundary relation also gives for different models having common boundary such as A, B, and C indicating how far the interpretations of the data have been made systematically.

Multi stratigraphic models are created and presented based on the conceptual model design in Table 5-8.

Figure 5-6 Multiple solid geology models with common boundary.

5.3.5 Factors controlling Interpretation for geological modelling

There are many factors affecting the final 3D geological model even when the data quality is guaranteed such as the scale problem, the geological complexity, size of grid cell (block cell) used, selection of different modelling algorithms, size of data set, selection of grid size in 2D (x,y) grid, z vertical spacing for sampling (modelling).

5.3.5.1 Modelling resolution

The word grid size has a synonymous meaning with node spacing and modelling resolutions. Determination of the suitable grid cell size (modelling resolution) in the modelling process is important because it affects the interpolation and extrapolation among data points. Variable resolution size from the same data set can be applied and the differences can be observed but sometimes the main difficulty is in storing all the constructed models and observing calculation processing, because of limitations in computer capacity (space), etc. In this study, selection of the grid cell in the vertical direction is based on the anticipated (observed) minimum thickness of the units.
There are two ways to insert the number of nodes to be created in the solid model. Either the model dimension reads automatically, or the program has been set up with grid model and solid model dimensions for that modelling project. This means that the program will always create grid models and solid models at the dimensions established under the View menu Project Settings option. The second option is manual input, introduction of the x, y, and z node spacing values every time of the modelling processes. Manual input is found to be more reliable for the modeling processes.

The summary table 5-9 presents the type of models created, possible grid sizes and different data sizes used for multiple solid modelling processes.

<table>
<thead>
<tr>
<th>Model</th>
<th>Type</th>
<th>Modeling resolution (m)</th>
<th>Algorithms</th>
<th>Data size%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model I</td>
<td>Chrono-stratigraphy</td>
<td>50x50x1 (A) 25x25x0.5 (B) 12.5x12.5x0.25 (C)</td>
<td>Inverse distance</td>
<td>100,90,50</td>
</tr>
<tr>
<td>Model II</td>
<td>Chrono-stratigraphy</td>
<td>50x50x1 25x25x0.5 12.5x12.5x0.25</td>
<td>Inverse distance</td>
<td>100,90,50</td>
</tr>
<tr>
<td>Model III</td>
<td>Chrono-stratigraphy</td>
<td>50x50x1 25x25x0.5 12.5x12.5x0.25</td>
<td>Inverse distance</td>
<td>100,90,50</td>
</tr>
<tr>
<td>Model IV</td>
<td>Chrono-stratigraphy</td>
<td>50x50x1 25x25x0.5 12.5x12.5x0.25</td>
<td>Inverse distance</td>
<td>100,90,50</td>
</tr>
<tr>
<td>Lith_strat</td>
<td>Litho-Stratigraphy</td>
<td>50x50x1 25x25x0.5 12.5x12.5x0.25</td>
<td>Inverse distance</td>
<td>100,90,50</td>
</tr>
<tr>
<td>Lith model</td>
<td>Lithology</td>
<td>50x50x1 25x25x0.5 12.5x12.5x0.25</td>
<td>Horizontal blending</td>
<td>100,90,50</td>
</tr>
</tbody>
</table>

Note that the numbers and figures used in the construction of models are based on the information given in Table 5-9.

The factors such as grid cell sizes, modelling algorithms and data size for each of the conceptual model design is considered.

**Conceptual Model I**: Geological geometry model shows two major formations based on the regional chronological order of formation:
- Westland Formation (Holocene Deposits) and
- Twente formation (Pleistocene Deposits)

Detailed descriptions for Westland and Twente formations have been presented in Table 5-6 and Table 5-7.
Figure 5-7 Solid geology models based on conceptual Model I using ID with different grid sizes: Model1_100A (50 x 50 x 1m), Model1_100B (25 x 25 x 0.5 m) and Model1_100C (12.5 x 12.5 x 0.25m), Vert. Exag. 100 X, SW view

Based on the resultant models above it appears visually that the boundary of two geological units is the same in the three models, and it can be concluded that, for general purpose regional assessment or mapping of the boundary of units, the grid cell size is less or not important.

**Conceptual Model II:** Three major units i.e., Upper Holocene (UHolocene Deposits), Lower Holocene (LHolocene), and Pleistocene are modelled in the conceptual model II. In this model the west land formation is subdivided into Upper and Lower Holocene (Table 5-8)

Figure 5-8 Solid geology models based on conceptual Model II using ID based on different grid sizes, Model2_100A (50 x 50 x 1m), Model2_100B (25 x 25 x 0.5) and Model2_100C (12.5 x 12.5 x 0.25m), Vertical exaggeration 100 x, Southwest view.

Comparing these models visually shows that, there are no significant differences of the geological boundary with variations of the grid cell sizes, but compared with the conceptual model I these models give more specific information in the upper part of the section.
Conceptual Model III: four geological units i.e., Upper Holocene (UHolocene Deposits), Middle Holocene (MHolocene Deposits), Lower Holocene (LHolocene Deposits), and Pleistocene (Pleistocene Deposits) are modelled.

Comparing the models in Figure 5-9, there are no significant differences of the geological boundary shape with variations of the grid cell size, but compared with the conceptual model II and I these models give more specific information in the Holocene formation.

Conceptual Model IV: Five geological units based on lithostratigraphic sequences of the area is shown as Tiel Deposits, Holland peat, Gorkum Deposits, Basal peat and, and Twente formation are modelled in this conceptual model.

These conceptual models (Model IV), represent more of the subsurface information as revealed and visualized in the previous works presented in Figure 5-3. The influence of modelling resolution is not clearly manifested as well as in the three respective models.
5.3.5.2 Modelling Algorithms

There are several methods offered to interpolate between the sample data. Each modelling method has strengths and limitations. In this research work, the modelling approach mainly used is based on Inverse Distance (ID).

Inverse distance (ID): ID method is one of the more common gridding methods. With this method, the value assigned to a grid node is a weighted average of either all of the data points or a number of directionally distributed neighbours. The value of each of the data points is weighted according to the inverse of its distance from the grid node, taken to a user-selected power. The greater the value of the exponent specified, the more localized the gridding since distant points will have less influence on the value assigned to each grid node. The Inverse-Distance method produces a smooth and continuous grid and will not exaggerate its extrapolations beyond the given data points. The formula is shown as below,

\[
Z_v = \frac{\sum \left( \frac{Z}{d^n} \right)}{\sum \left( \frac{1}{d^n} \right)}
\]

In assigning node values, the value of each data point is weighted according to the inverse of its distance \( d \) from the grid node, taken to the nth power, as shown in the formula, above.

By raising the distance factor in the denominator to a power greater than one, the values of distant data points will exert less influence than nearby points on the value assigned to the grid node. The greater the value for the exponent, the less influence these distance points will have.
The differences and effects on the result and models by different algorithms on the same dataset are discussed in chapter 6.

5.3.5.2 Reduction of the data size

Generally, in the case of homogeneous geological conditions the resultant 3D models based on the limited number of boreholes are reliable. However as expected, in a complicated sedimentary environment, the number of boreholes is important for building a reliable subsurface model. In this section the original data set is reduced by 10% and 50% respectively.

Considering the irregular distribution of the 63 boreholes in the test area (Figure 5-13), there are tens of thousands possibilities to reduce the data size. To tackle this problem, artificial grid lines are designed along x and y directions as shown in Figure 5-13, an irregular distribution of holes. 10% and 50% of the boreholes are randomly picked off for the modelling as shown in Figure 5-14A, and Figure 5-14B respectively. Figure 5-11 compares the resultant models based on the conceptual model of different data sizes.

![Figure 5-11 Solid geology models based on conceptual Model IV using ID algorithms, Model 4 on different data sizes: Model4_100A (50 x 50 x 1m), Model4_90 (50 x 50 x 1m), Model4_100C (50 x 50 x 1m), Vertical exaggeration 100 x , Southwest view.]

The model base on different numbers of boreholes indicates that the boundaries of units are not clearly depicted if based on 50% of the boreholes. A model with only 50% of the number of boreholes does not reveal very detailed information on the boundary and thickness of units; there are not many differences if the model is based on 90% of the number of boreholes instead of 100%.
According to the statistical analysis result, there is a significant difference in the volume of material depicted during the omission of the 50% of the boreholes. The variation in results is logical and acceptable due to the sensitivity of assumed the constitutive model to the number and position of boreholes omitted. This has consequences for the spatial variability of geo-object in lateral and vertical extension.

Note that for models Model I, II, & III, the resultant models and compared results are attached respectively in Appendix IV.

After omission of 10% of the number of boreholes, 57 boreholes were used for the litho models the holes omitted are shown in Figure 5-14A. The three solid models presented in figure 5-11 are based on 90% of the number of boreholes with different modelling resolutions. In the geology model of 90% borehole reference points is indicated with circle in Figure 5-11 to see the similarity in boundary features. It seems that, Model4_100A (50 x 50 x 1m) and Model4_90 (50 x 50 x 1m), are nearly the similar. For detailed information about modelling resolution and different data sizes refer Table 5-9.

The models based on 50% of the number of boreholes are presented in Appendix III-4. The three models of model4_50, with resolutions A, B, and C show very slight differences in the intensity of feature resolution. In the circle indicated for references, the sharpness of the peak of boundary of unit gradually diminishes towards 50A. This indicates that the wider the grid sizes in 50A the higher the chances of categorizing the cells of different units grouped as one cell, whereas in 90C the cells are separated since higher resolutions favour the splitting of different units into different grid cells.
Figure 5-13 segment shown with distribution of hole in each designed cell

Figure 5-14 Location of omitted boreholes: circle indicates 10% omitted, cross symbol indicated 50% of the boreholes omitted

5.3.6 Geotechnical property modelling

3D geotechnical models can provide information on the spatial variation of the properties but also directly facilitate geological models. In this study, the unit weight is selected for constructing 3D geo-
technical subsurface models. Since no unit weight is available from a sample test in this particular area of units (Clay, peat sand), the values of the average unit weights were used from a standard booklet established for (Dutch soil classifications NEN 6740), Zigterman, et al 2001. As it has been recommended in the manual, representative values of average properties of a soil layer may be applied if no lab tests have been carried out for a particular area in a particular unit.

This type of approach has been adopted by Toll et al. 1993: the geotechnical parameters can be assessed in three ways: from direct measurement, from correlation with other test areas or from the engineering description of the ground.

The average unit weights of three types of soil units in the study area are listed in Table 5-10. These are used to reconstruct the geotechnical property of the subsurface.

Table 5-10 Shows the unit weight of soil in the test area (according to NEN 6740)

<table>
<thead>
<tr>
<th>Soil unit</th>
<th>Unit weight (saturated) (KN/m³)</th>
<th>Unit weight (Dry) (KN/m³)</th>
<th>Porosity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Range</td>
<td>Average</td>
<td>Range</td>
</tr>
<tr>
<td>Sand</td>
<td>18.5-21.5</td>
<td>20</td>
<td>18.5-21.5</td>
</tr>
<tr>
<td>Recently deposited clay</td>
<td>11.5-17</td>
<td>14</td>
<td>2.5-11</td>
</tr>
<tr>
<td>Soft clay</td>
<td>15-18.5</td>
<td>16</td>
<td>8-13.5</td>
</tr>
<tr>
<td>Peat</td>
<td>10-14</td>
<td>12</td>
<td>0.5-7</td>
</tr>
</tbody>
</table>

The result of the property distribution shows a pattern (Figure 5-15) that can directly be related to an actual ground conditions. It can be used to distinguish some anomalous lines (network) that indicate different geo-objects. For example a buried drainage line, shown by the arrow in figure 5-15 100A, and circular features of variable sizes shown in figure 5-15,100C. The latter may indicate depressions and possibly marshy areas.

In general it is also possible to distinguish areas with high potential for settlement. For example, the area indicated by the arrow in figure 5-15,100B. In this area, unit weight is low which likely means that also the specific gravity is low and this may be related to susceptibility for compression or ground settlement problems.
As far as the average unit weight of the major units is used for the property modelling, by reinterpretation of the data and considering different scenarios, slightly different results are achieved as presented in Figure 5-15 and Figure 5-16. For example Figure 5-15, the soil unit with the highest density (pinkish colour) at the base of the units is missing in model 100A, indicating that the grid size or modelling resolution is too wide and minor layers are not separated. As the resolution is becoming high the spatial variation of properties at a small distance are better visualized. It is a matter of reinterpreting the original data till it is correlative logically with assumed actual ground data based on existing previous works, cross-sections (Figure 5-2 and 5-3).

Multiple Geotechnical property models (dry unit weight) of the geological units have been presented in Appendix, VII based on 90%, 50% and 100% number of boreholes and model resolutions.

5.3.6.1 Role of unit weight for prediction of settlement

Among the most important parameter in the geo-technical assessment for the settlement consideration is the density of the material. To visualize the areas susceptible to ground settlement, a modelling
process of a geo-technical property has been adopted. Each cell representing a unit is assigned a mate-
rial type number (unit weight value) and with variable material types, to be used gradual changes of 
the property guide the position and direction of soft materials.

Generally, the material properties of soils are set up in two basic conditions:

- Material type (unit type)
- Density
  - Dry density - the average total unit weight above the phreatic surface.
  - Wet density - the average total unit weight below the phreatic surface

Dry density of the soil material is calculated as:

\[ \gamma_d = \frac{W_s}{(V_s + V_w)} \]  

In which

- \( \gamma_d \): dry unit weight,
- \( W_s \): weight of solid
- \( V_s \): volume of solid, and
- \( V_w \): volume of water

Since the data about the position of the phreatic level in the study area are not available, the average 
unit weight of saturated soil and dry unit weight are separately used for modelling. In general, there is 
a possibility of having the same value of saturated unit weight for different soils but the dry unit 
weight is always different for different soil. Therefore, the average value of dry unit weight of soil 
units in the area may be considered as an important parameter to differentiate property features in a 
horizontal and vertical dimension.

![Figure 5-17 Model geo-tech 100A model, cross section along NNW_SSE of the test area](image)

Figure 5-17, shows a vertical section selected along a line NNW-SSE direction through the study area, 
the main rivers flow from east to west. The section perpendicular to the flow of the drainage line 
should expose more representative units than sections parallel to the main rivers.

It is clear that the result is fully in agreement with this. It indicates that the property model result is 
matches with the actual ground section shown in the Appendix II. In the geo-technical subsurface
modelling, it is therefore, prudent to use the property models to show features responsible for the variability of the properties. For an enquiry of detailed information with respect to changes in property of geo-objects in vertical or lateral spatial orientations, the approach is easy to adopt and simple to interpret the results.

The second section is selected along a line running NNE-SSW crossing nearly the central part of the area. As it has been shown in the section below, in Figure 5-18, that regularly spaced bore hole data can be well interpreted using property value of the subsurface geo-objects.

![Figure 5-18 Shows an overlay of hole log to vertical profile along A-B of the test area.](image)

Different vertical profile sections are constructed also to see the differences in the results, using different bore hole numbers (50%, 90% and 100%) and modelling resolutions (A, B, and C) are presented in Appendix VII: 2

### 5.4 Discussion

The geo knowledge reasoning approach is adopted in the modelling process to generate or create subsurface geo-objects. Models are built for any particular objective or a specific job. To investigate the suitability of different possible scenarios, multi models have been built. Each of these can be used for different purposes. The method followed is from a very general (simple) approach to a complex (more realistic) situation.
Visualising the result in different perspective views in observation of the same data with variable data size will show the differences with respect to view direction and information on the real situation in the ground. Each of the perspective views may be useful for understanding the problems related to spatial variability of the geo-object in space.

The relationship of individual geo-objects with the level of information content on the lateral and vertical continuity of units and their interrelationships can be judged by experienced professionals or the person who conducted the construction of multi models.

The presence of lenticular sand intercalated within an extensive clay layer exposed in the northeastern part of the area can be an indication of its origin as fluvial or buried channel in a marine environment.

The use of Rockworks 2002 software for the subsurface 3D models and visualization is very good and easily manageable, but there are certain rules and regulations set to be followed. For example in the use of the lithology and the stratigraphy tables for importing the data, solid modelling process, the regulations to be implemented are summarized in Table 5-11.

Table 5-11 Differences of lithological and stratigraphical modelling in Rockworks2002

<table>
<thead>
<tr>
<th>Lithology Model</th>
<th>Stratigraphy Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 The first step in modelling process</td>
<td>The second step</td>
</tr>
<tr>
<td>2 Represent observed rock type</td>
<td>Interpreted layers or formations</td>
</tr>
<tr>
<td>3 Repeated sequences allowed</td>
<td>No repeated sequence</td>
</tr>
<tr>
<td>4 No lateral variability</td>
<td>Has lateral variability</td>
</tr>
<tr>
<td>5 Data is entered in lithology tab</td>
<td>Data is entered in stratigraphy tab</td>
</tr>
<tr>
<td>6 No correlation is possible in hole to hole vertical section</td>
<td>Correlation is possible in hole to hole vertical section</td>
</tr>
<tr>
<td>7 Is modelled as solid model using the &quot;lithoblende&quot; algorithm for display as profiles, fences, and block diagrams.</td>
<td>Layers are modelled as surface (grid) models, using different algorithms of choice for display as profiles, fences, and block diagrams.</td>
</tr>
</tbody>
</table>
6 Comparison of models

6.1 Introduction

In the foregoing chapters is shown that, multiple geological models can be constructed for a specific modelling purpose based on a limited amount of data. However, judging the accuracy of the models generated by the modeller is difficult if not impossible. The model constructed of the subsurface may look beautiful, but it does not necessarily mean that the interpretation of the data is good and reliable. Quantification of the likelihood of the models, however, is crucial for the follow-up engineering design and risk assessment. In chapter 3, several methods of validating 3D models have been presented. In this chapter, the created lithological and stratigraphic models made based on the Reeuwijk data set are compared to find differences in the nature of boundaries, thickness, and volume of units in different modelling scenarios.

6.2 Comparison criteria

Comparisons of the lithological and stratigraphic models are done according to criteria such as visual inspection (variation boundaries between lithological or geological units) and statistical parameters (thickness and volumes of layered beds).

6.2.1 Variation of boundary

The models can be compared based on the common features, i.e., the boundary of units. In Figure 5-8, three topological lines are used for the comparison.

- Boundary A: presents the common boundary among the conceptual model 2, 3, and 4
- Boundary B: presents the common boundary between the conceptual model 3 and 4
- Boundary C: presents the common boundary among conceptual models 1, 2, 3, and 4.

It is clear that the boundary between Holocene and Pleistocene in all the models shows similarity.

6.2.2 Thickness of units

The visual inspection of the thickness of units in the conceptual models shows that they are not the same or similar. Figure 5-11, presents the effect of variable bore hole number on the thickness of units. Models based on a reduced number of boreholes show more variation in lateral consistency as well as in the thickness of the units.

6.2.3 Volume comparison
The volume of combined units or of a specific unit can also be used for comparing models. The difference will show the effect resulting from the changed interpretation parameters, such as modelling resolution, data size and modelling algorithms. The result is presented in the following section.

### 6.3 Comparison of lithological Models

Models are compared and evaluated in two ways:

- Comparing the interpreted lithological sequence with an existing cross-section of the region (Figure 5-2 and Figure 5-3)
- Comparison of the models based on different sizes of data set (here 100% and 90% and 50% of number of boreholes).

The estimated volume, and histograms are based on different modelling resolution and are presented in Figure 6-3.

From this graph, it is clear that different lithological units show different volume in different resolutions, indicating that as the grid size became small, patches of units can be seen separately or included in the volume calculations. Detailed results are mentioned in the coming sections.

#### 6.3.1 2D/3D visualization

Drawing an arbitrary planar or sectional view through the model is a very important step for validating the interpretation processes. Each kind of the unit boundary and its association with other units can be visualized and compared with known profiles. Figure 6-1A gives the 3D view of total 63 boreholes with the spatial position, orientation and relations of lithological units.

Figure 6-1B is an example of a section through the lithological model. It shows that the litho sequence, i.e., clay, peat and sand along the vertical direction corresponds with general litho stratigraphic sequences of the western part of The Netherlands (Table 5-6). The irregular distribution of the peat unit indicates that there is a complicated deposition environment. In addition, there are some lenticular sand layers within the peat unit, which probably indicates the fluvial deposition originally connected to the bottom sand layer.
6.3.2 Lithological fence diagram

The lithological fence diagrams as shown in Figure 6-2 can also assist to understand the distribution of units in 3D space, which in turn guide the interpretation of the stratigraphic units. With the smaller grid size used in the modelling, some smaller units appear.

Figure 6-2 Fence diagrams of the lithology with grid sizes of 50 x 50 x 1m (A) 25 x 25 x 0.5m (B) and 12.5 x 12.5 x 0.25m (C), vertical exaggeration 100x, southwest viewing direction from above.
6.3.3 Comparison of Lithological Unit Volume

Figure 6-3 shows the result of lithological unit volumes from three models generated by different grid sizes based on 100% of the data set. It is clearly seen that no significant difference of volumes among the three models occurs. It is concluded that for the study area changing the modelling grid size does not result in the volume change of lithological units.

![Litho_unit volume comparsion (Grid size)](image)

Figure 6-3 Litho unit, volume comparisons of model 100% data set with grid spacing of 50 x50 x 1m (A), 25x25x0.5 m (B), and 12.5x12.5x0.25 m (C).

6.4 Comparison of stratigraphic Models

As described in chapter 5, four conceptual chronostratigraphy models are built for different modelling purposes. Within each kind of the conceptual models, multiple geological models can be constructed based on a different model grid size or resolution, and modelling algorithm. Considering that conceptual model 4 is very close to the realistic situation of the modelled geo-objects, the comparison of the geological models based on this conceptual model is given in this section. The comparison results based on the other three conceptual models (I, II and III) are attached in Appendix III.

6.4.1 Stratigraphic models built from variable grid sizes

Figure 6-4 shows the histograms and statistical results of the three stratigraphic models generated from different grid sizes (25 x 25 x 0.5 m$^3$, and 12.5 x 12.5x 0.25 m$^3$). There are differences in volumes between the models, especially the model with the low resolution. In the case of the lower grid size, hence the model with the least resolution i.e., 50 x 50 x 1m (Model 4_100A), the volumes of the Tiel deposits, Holland peat, Gorkum deposits and Basal peat are the largest and diminish if the grid size comes smaller. There are no significant volume differences between Model4_100B and Model4_100C.
6.4.2 Volume comparison of models by different data amounts

To illustrate the effect of reducing the number of data size used for the modelling, the stratigraphic models are constructed, after omission of, 10% and 50% of the number of boreholes. Other parameters are kept same. Figure 6-5 and Figure 6-6 present the histograms and statistical summary of the resulting models.

It is found that not much difference occurs between the models using 90% and 100% of the boreholes. This indicates that omitting 10% of the number of boreholes can achieve similar result in the same investigation time. However, there is a large difference between the models generated by 50% and 100% of the number of boreholes.

Figure 6-5 Model 4 volume comparisons on 90% borehole data, grid sizes of 50x50x1 (A), 25x25x0.5 (B), and 12.5x12.5x0.25 (C)
Figure 6-6 Model 4 volume comparisons on 50% data set, grid sizes of 50x50x1 (A), 25x25x0.5 (B), and 12.5x12.5x0.25 (C)

6.4.3 Thickness comparison

The 2D thickness map of Holland peat is used for the comparison processes of the variations in the modelling resolutions. Figure 6-7, 6-8 and 6-9, show the thickness of the Holland peat modelled with different grid cells (A, B, and C), for model 4 stratigraphy showed differences. As the grid size becomes finer, separation of peat unit to different thickness classes at different places is clear. The 3D view of the Holland peat presented in Figure 6-13 is also used to look for uniformity or variations in thickness at different places.

Figure 6-7 2D thickness map of Holland peat, Model4_100A (50x50x1) using ID
The three-dimensional view of the Holland peat is presented in Figure 6-10. The result shows that the thickness of Holland peat varies from place to place. Though vertical exaggeration introduced in the conceptual model 4 is 100x, undulating surfaces show that there is a significant variation of thickness i.e., in the order of 0 to 5 m as can be observed from the contour map in Figure 6-7.
6.5 Litho-stratigraphy model

Rockworks 2002 doesn’t allow the dictation of repetitive material layers in the stratigraphy utility. This limits the possibilities for modelling, therefore all of the stratigraphic models created in stratigraphic model cannot reflect the realistic situation, and the geological boundaries are heavily smoothed. Comparison results of chronstratigraphy and litho stratigraphy sections are attached in Appendix VI: 1 and 2 respectively. In case of the chronstratigraphy model the boundary between units show sharp and smooth lines, which is not common to natural conditions however in the litho stratigraphy section, boundaries of layers show blocky and rough with irregular surfaces.

Figure 6-14 shows the 3D view and fence diagrams of the interpreted geological units. From the diagram, it can be seen that the spatial distribution of different units is more reliable than those represented in the stratigraphic model generated in the stratigraphic model (Figure 5-10).

Figure 6-11 3D views of interpreted geological units along boreholes and created fence diagram

Figure 6-12 shows the litho-stratigraphic models with different resolution degree. It is shown that the model 4_lith100C has the highest resolution of displaying details of the geological units than the other two models.

Figure 6-12 Lithostratigraphic model 4_lith100A, 100B and 100C
Compared with the conceptual stratigraphic models in Figure 5-6, the litho-stratigraphic models give more detailed information of the units. Note that features in a circle indicated in figure 6-12 100B to compare the importance of modelling resolutions in 100C. In case of 100C detaileds of minor units are separated as indicated in the triangular symbol.

### 6.6 Effects of modelling algorithms

As discussed in chapter 2 there are different modelling approaches for constructing multi-models, however, the selection of appropriate algorithm is normally based on user-defined criteria. There is no standard for guiding the selection, but in common practice, inverse distance is mostly used for 3D subsurface modelling.

Although the inverse distance-modelling algorithm is used in this study, the models constructed using closest point (Figure 6-13) and Kriging (Figure 6-14) are presented using different filter sizes. The variation in filter size makes differences either in the sharpening of features or smoothing anomalies. The differences are very clear in the figures indicated below (Figure 6-13, 6-14 and 6-15).

**Figure 6-13 Model4_100A, Closest Point Algorithm, with filter sizes, (2x2) left and (1x1) right**

**Figure 6-14 Model 4_100A using Kriging with filter sizes of 2 x 2 left and 1x1 right**
Figure 6-15 Model4_100A Inverse distance with filter sizes of 2x2 left and 1x1 right.

6.6.1 Conclusions

1) The assessment of the generated models can be realized by the visual inspection of the 2d section and fence diagrams in aspects of the boundary variations of units and their spatial associations of different geological units. The re-interpretation is conducted whenever the doubt exists as to differences in stratigraphic sequences leading to a reasonable model.
2) The comparison of constructed models is also possible by comparing the thickness and volume of the individual unit.
7 Assessment of Likelihood of G² Models

7.1 Introduction

In this chapter the likelihood index assessment approach is presented, i.e., semantic ranking approach and the application of the proposed approach is illustrated in this case study. Whenever models are available, the first question that comes to mind is its reliability. However, the assessment of reliability of the subsurface 3D model depends on the type of geo-object and the quality and type of parameters used in the modelling process. In this study, the factor involved in the modelling process is discussed, and then the semantic likelihood index assessment approach is proposed.

7.1.1 Factors involved in the likelihood index

Many possibilities exist for the reconstruction of the 3D subsurface geo-objects, and many factors are involved in the modelling process. In this study, three categories of factors are summarized for the assessment of the likelihood of the model reliability, which can be taken as the likelihood assessment index.

- Data quality and quantity (data type, amount of samples, scale of investigation, etc.)
- Interpretation quality (education, professional experience and skill etc.)
- Selection of modelling algorithms (Inverse distance, nearest point, kriging, etc.)

Logically, to get more reliable and fairly representative subsurface models, the most important parameters to be considered in the modelling process should be considered and quantified. However there is no mathematical formula for the quantification of knowledge involved in the data collection phase and in the modelling process. Therefore, there is no easy and straightforward method to find the relationship to convert subjective ideas (knowledge) into numbers to quantifying reliability. Although the parameters involved may not have the same contribution to reliability, all are important in the assessment of the reliability of a model. Priority ranking may be biased but at least gives an idea for focus. Based on subjective reasoning and professional judgments, the role and levels of above-mentioned three parameters are presented as follows:

Data quality and quantity

In a given investigation or exploration project, the quality of data is the base for the success. So the data quality is given first priority, because if the data to be used in the characterizations of the subsurface geo-object is not very good, it has no meaning to proceed with the next stage of the work. Many researchers have contributed to the quantification of data errors.

Interpretation quality
The second important parameter, e.g. a systematic interpretation from multi sources data of different scale and collected in different periods, is difficult to quantify qualitatively. Using the same data set, different professionals do get different results, so interpretation quality is an important element to be considered and possibly to be judged and quantified in the process of a modelling system in the interpretative manner.

**Selection of modelling algorithms**

The third important parameter also contributes to the differences in the models. The resultant stratigraphic models by different algorithms are discussed in the section 6.6

Potential relations and mathematical computations are only possible if the three categories of the proposed parameters are quantified. To quantify the quality or importance levels, it needs a standardized method or approach that can directly differentiate the quality and degrees of different levels (Table 7.5). To solve this, a semantic approach is proposed to assess the likelihood of the 3d subsurface models as follows:

\[
\begin{pmatrix}
D_1 & D_2 & D_3 \\
I_1 & I_2 & I_3 \\
P_1 & P_2 & P_3
\end{pmatrix}
\]

(1,2,3 represents very good, good, fair respectively in terms of data quality)

(1,2,3 represents very good, good, poor respectively in terms of interpretation)

(1,2,3 represents most commonly, rarely, uncommon respectively in terms of algorithm selection).

Data Quality: D represents first priority parameter
Interpretation quality: I represent second priority parameter.
Model parameter: P represents third priority parameter

To find the relationship between different parameters and a combination of these factors, the matrix calculation should be deduced and 27 possible combinations are expected in this case. However, to conduct the matrix calculation requires the definite value for each parameter. How to assign the value or give the subjective ranking score for each parameter depends on many factors. This will be discussed in the next section.

**7.1.2 Likelihood assessment principles**

The method addresses uncertainty in both numeric and semantic data inputs and in technical and non-technical issues. According to Bowden (2003), the inclusion of human judgment in the interpretation process means that there will be frequent differences of opinion and the ability of alternative, inconsistent and/or conflicting interpretations. Much of the value of the method is in identifying uncertainties explicitly as:
• Knowledge based (through ignorance or lack of knowledge)
• Conflict based (through differing value judgments)
• System based (through randomness or system heterogeneity) or
• Indeterminate (through future system behaviours)

It is most likely that a relatively reliable model can be built from the data in the study area because:
• The use of an accepted existing data base of NITG_TNO
• The existence of relatively densely spaced boreholes with detailed descriptions of each unit and sampling depth,
• An integration of geo-knowledge base reasoning framework with available previous results (reports, maps, sections, oral communication with respective supervisors).
• The easy operational 3d modelling systems (Rockworks 2002)

7.1.3 Semantic geo-reasoning framework

Before analysis of methods, and factors contributing to the system, the principles of likelihood in relation to other fields are considered, especially to mathematics and logics. What is the relationship between geo-reasoning based logic and mathematics?

A violent discussion on what is primary, logic or mathematics, lasted throughout the 1940’s and 1950’s among the followers of logician Hilbert and mathematician Egbertus and Jan Brouwer and has not reached a final agreement Pshenichny(2003). It seems plausible that both are complementary rather than competing and forms a continuum of methods formally to any other human knowledge. A conclusion reached later by Zadeh (1995) that, from the polemics of statisticians and fuzzy logicians; the "border" between logic and mathematics in any given domain of knowledge (e.g., geosciences) is an open question Pshenichny (2003)

Although quantification of the subjective knowledge is very difficult and has no direct proof, there should be a common level at which most professionals can agree. Quantification of likelihood (reliability) of the created model could be judged by the likelihood index (discussed in the following section).

Verification for the reliability of subsurface models can only be possible either by direct way of proof, if the volume under investigation is excavated and exposed or by indirect methods by comparison of different source data sets like bore hole geological or geo-technical logging (hard data) and from geophysical data (soft sources). Direct verification is normally done simultaneously with the actual construction activities in case of underground constructions or exploration. If excavation is not possible or not the purpose for which the model has been made verification is only possible by interpretation of an integrated multi sources data system.

7.1.4 Likelihood index input parameters
As mentioned in Section 7.1.1, three categories of basic parameters need to be considered for quantification of likelihood of the created models. Each of them is described in detailed in Table 7.1,7.2 and 7.3 respectively. The assessment procedure is as follows:

- To define the modelling objectives properly and establish the standard format which can satisfy the idea of professional experts
- To gather the opinions from different professional experts by questionnaires
- The third step is to organize different opinions systematically and assign the weighting score for each parameter either by the verbal method or statistical methods
- The fourth step is to sum up the reasoning result from the data quality, interpretation quality and modelling parameters and give the final ranking of the model.

7.1.4.1 Data parameter index

Data quality is assessed based on the types of available quantititative data, and accuracy of each data set as shown in Table 7-1:

- Standard data collection format used for the specific work for international/national projects (well established data base format).
- Collection of data by professional workers (experience of involved professionals)
- Supervised and checked by senior staff regularly
- Systematic data validation system for analytical samples and data transforming error.

Table 7-1 Data quality parameter element and associated rating values

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Elements</th>
<th>Rating</th>
<th>Total Score</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Data quality</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Surface Information</td>
<td>Physical</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Biological</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Chemical</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Outcrop</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. Subsurface Data</td>
<td>Core log</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Well log</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Geo-technical test</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hard Data</td>
<td>(CPT)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Geophysical survey</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soft Data</td>
<td>Geo-chemical survey</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Remote sensing data</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Production history</td>
<td>Mining, construction</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

7.1.4.2 Interpretation quality parameter
The interpretation quality is affected by many factors as discussed in Chapter 3. In this study, the main five aspects influencing the interpretation are summarized shown in Table 7-2. The detailed aspect is discussed in chapter 3.

7.1.4.3 Selection of Modelling algorithms

In chapter 2 the main modelling approaches are summarized for the modelling geo-objects (geometry and property). The selection of the modelling is based on the application assumption and the practical situation. Therefore, the subjective factor for selecting the modelling algorithm can be assigned based on the common application case and professional judgment. Table 7-5 lists main factors involved in the selection of modelling methods, and can guide the index assessment of model likelihood affected by the limitation of modelling algorithm.
Table 7-2 Interpretations quality parameter elements and associated rating values

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Elements</th>
<th>Rating</th>
<th>Score%</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1. Scale/objective (User-defined)</strong></td>
<td>Site</td>
<td>10-100m</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Site</td>
<td>100-5,000m</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Regional</td>
<td>5000-100,000m</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Global</td>
<td>&gt;100,000m</td>
<td></td>
</tr>
<tr>
<td><strong>2. Geological Environment</strong></td>
<td>Marine</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Continental</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fluvial</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Inter-marine and continental</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>3. Geo_object Modelled</strong></td>
<td>Hard Geo-object</td>
<td>Single</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Definition-limited geo-object</td>
<td>Multiple layer</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Based on economic grade (ore body)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>4. Spatial extents (x, y, z)</strong></td>
<td>Horizontal continuous</td>
<td>Simple (horizontal layer, slightly curved)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Complicated (wavy)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Non continuous (lense, intercalation, infringing)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Vertical continuous</td>
<td>Distinct layers</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Multi repeating layers</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>5. Geological process/time</strong></td>
<td>Normal</td>
<td>Original in-situ position</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Complicated</td>
<td>Dislocated due to tectonics (subsiding, uplifting man made etc)</td>
<td></td>
</tr>
</tbody>
</table>
Table 7-3 Modelling algorithm selection criteria

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Elements</th>
<th>Rating</th>
<th>Total Score%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Geological complexity</td>
<td>Simple (not disturbed)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Complex (Disturbed)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. Investigation density</td>
<td>&lt;10x20m</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>10x20m-20x40m</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>20x40m-40x80m</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>40x80m-80x120m</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>&gt;80mx120m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. Model Resolution</td>
<td>&lt;5x5m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(grid size-x and y)</td>
<td>5x5m-25x25m</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>25x25m-50x50m</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>50x50m-100x100m</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>&gt;100mx100m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. Resolution (Grid size, z)</td>
<td>0.25</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 7-4 Modelling algorithm selection criteria (Cont.)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Type of Modelling</th>
<th>Algorithm</th>
<th>Rating</th>
<th>Total Score%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Volume Modelling</td>
<td>Surface Representation</td>
<td>Boundary representation</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Constructive solid geometry</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>NURBS</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Volume Representation</td>
<td>Voxel</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Octree</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Geo-cellular</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Iso-surface or Grid</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Inverse Distance</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Close point</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. Stochastic simulation</td>
<td></td>
<td>Sequential indicator simulation</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Boolean simulation</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Simulated Annealing</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
So, the final quality rank of the model likelihood can be reasoned based on the results of the above-mentioned three parameters as shown in Table 7-5.

Table 7-5 Geo-reasoning based quality ranking for the model parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Qualitative rating</th>
<th>Quantitative range %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td>Excellent</td>
<td>90-100</td>
</tr>
<tr>
<td></td>
<td>Very good</td>
<td>75-90</td>
</tr>
<tr>
<td></td>
<td>Moderately good</td>
<td>50-75</td>
</tr>
<tr>
<td></td>
<td>Fair</td>
<td>25-50</td>
</tr>
<tr>
<td></td>
<td>Poor</td>
<td>&lt;25</td>
</tr>
<tr>
<td>Interpretation</td>
<td>Extremely good</td>
<td>90-100</td>
</tr>
<tr>
<td></td>
<td>Very good</td>
<td>75-90</td>
</tr>
<tr>
<td></td>
<td>Moderately good</td>
<td>50-75</td>
</tr>
<tr>
<td></td>
<td>Fair</td>
<td>25-50</td>
</tr>
<tr>
<td></td>
<td>Poor</td>
<td>&lt;25</td>
</tr>
<tr>
<td>Model Algorithms</td>
<td>Extremely fitting</td>
<td>90-100</td>
</tr>
<tr>
<td></td>
<td>Very good fitting</td>
<td>75-90</td>
</tr>
<tr>
<td></td>
<td>Moderately fitting</td>
<td>50-75</td>
</tr>
<tr>
<td></td>
<td>Fairly fitting</td>
<td>25-50</td>
</tr>
<tr>
<td></td>
<td>Not fitting</td>
<td>&lt;25</td>
</tr>
</tbody>
</table>

The likelihood level of models can be arbitrarily classified into the four integral levels (Table 7-6), which can be used for the risk assessment in the later stage after the geo-object model has been constructed. The scale ranging from 1 to 4 indicating the highest degree of likelihood to the most unlikely models respectively.

Table 7-6 Levels of likelihood

<table>
<thead>
<tr>
<th>Qualitative</th>
<th>Semi-quantitative</th>
<th>Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Most likely</td>
<td>&gt;90</td>
<td>1</td>
</tr>
<tr>
<td>Very likely</td>
<td>75-90</td>
<td>2</td>
</tr>
<tr>
<td>Moderate</td>
<td>50-75</td>
<td>3</td>
</tr>
<tr>
<td>Unlikely/Negligible</td>
<td>&lt;50</td>
<td>4</td>
</tr>
</tbody>
</table>

7.1.5 Ranking of likelihood of subsurface models

The proposed likelihood index assessment is tested in the Reeuwijk area. The final result for the likelihood index of the Construction of the subsurface geo-objects can be obtained by the weighted average values obtained from the three parameters mentioned in (Table 7.1,7.2 and 7.3). Considering the model built of moderate data quality, and modelling algorithms, interpretation quality varies based on
the modelling resolutions (A, B, and C). The results of ranking multi lithological and stratigraphic models in this study are summarized in Table 7-7 and Table 7-8 respectively.

Table 7-7 presents the ranking result of chronostratigraphy and lithostratigraphic models based on the conceptual model IV with 100% of the number of boreholes and a modelling resolution of 12.5 x 12.5 x 0.25 m$^3$. The lithostratigraphic models are considered to represent the subsurface information relatively accurate (at least as accurate as is possible with the data set) as compared with chronostratigraphy models.

Table 7-7 Ranking of the multi models based on the conceptual model IV

<table>
<thead>
<tr>
<th>Conceptual Model IV</th>
<th>Chronostratigraphy Model 4</th>
<th>Lithostratigraphy Model 4_lith</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4_100A</td>
<td>4_100B</td>
</tr>
<tr>
<td>Data Q %</td>
<td>50-75</td>
<td>50-75</td>
</tr>
<tr>
<td>Inter Qual. Resolution</td>
<td>25-50</td>
<td>50-75</td>
</tr>
<tr>
<td>M.Selection</td>
<td>50-75</td>
<td>50-75</td>
</tr>
<tr>
<td>Model ranking</td>
<td>Scale</td>
<td>4</td>
</tr>
</tbody>
</table>

For the stratigraphy modes (Table 7-8) based on the conceptual model 1, different units lumped together according to their chronological order in the visualization produced, it shows a situation not likely conforming to the natural conditions, so these models are not reliable compared with those geological models obtained from the conceptual model 4. However, for the purpose of studying the stratigraphic boundary of the Holocene and Pleistocene, they have equal important quality as those in model 2, model 3 and model 4 (Figure 5-6).

Table 7-8 Ranking of multi lithological and stratigraphic model based on conceptual model

<table>
<thead>
<tr>
<th>Conceptual Model 1</th>
<th>Solid lithology</th>
<th>Stratigraphy Model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Lith 100A</td>
<td>Lith 100B</td>
</tr>
<tr>
<td>Data Q %</td>
<td>50-75</td>
<td>50-75</td>
</tr>
<tr>
<td>Interpretation quality (resolution)</td>
<td>50-75</td>
<td>75-90</td>
</tr>
<tr>
<td>Model selection</td>
<td>50-75</td>
<td>50-75</td>
</tr>
<tr>
<td>Model Ranking</td>
<td>Scale</td>
<td>3</td>
</tr>
</tbody>
</table>

The summary result of the study area with parameters involved and factors contributed in each modelling system are presented in Table 7-9.
### Table 7-9 Summary of the test area parameters with the possible likelihood of models on different scenarios

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Reeuwijk Road Project</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Conceptual Model</strong></td>
<td></td>
</tr>
<tr>
<td>Model 1</td>
<td></td>
</tr>
<tr>
<td>Model 2</td>
<td></td>
</tr>
<tr>
<td>Model 3</td>
<td></td>
</tr>
<tr>
<td>Model 4</td>
<td></td>
</tr>
<tr>
<td><strong>Model units</strong></td>
<td></td>
</tr>
<tr>
<td>2 units</td>
<td></td>
</tr>
<tr>
<td>3 units</td>
<td></td>
</tr>
<tr>
<td>4 units</td>
<td></td>
</tr>
<tr>
<td>5 units</td>
<td></td>
</tr>
<tr>
<td><strong>Area</strong></td>
<td>3.2 km²</td>
</tr>
<tr>
<td><strong>Borehole</strong></td>
<td>63 shallow holes (max 9m)</td>
</tr>
<tr>
<td><strong>Geophysical</strong></td>
<td>no</td>
</tr>
<tr>
<td><strong>Regional geol.</strong></td>
<td>Detailed regional geol. Information (map, cross sections, reports)</td>
</tr>
<tr>
<td><strong>Geotechnical</strong></td>
<td>Some CPT data, many CPT holes outside the test area, unit weight (NEN 6740)*</td>
</tr>
<tr>
<td><strong>Scale</strong></td>
<td>Site Scale</td>
</tr>
<tr>
<td><strong>Geo. Environment</strong></td>
<td>Fluvial/marine environment</td>
</tr>
<tr>
<td><strong>Geo-object</strong></td>
<td></td>
</tr>
<tr>
<td>Single units</td>
<td></td>
</tr>
<tr>
<td>Multiple units</td>
<td></td>
</tr>
<tr>
<td>Multiple units</td>
<td></td>
</tr>
<tr>
<td><strong>Spatial extent</strong></td>
<td>Continuous</td>
</tr>
<tr>
<td></td>
<td>Continuous</td>
</tr>
<tr>
<td></td>
<td>Lower Holo (Basal peat and Gorkum deposits) not continuous, other units continuous</td>
</tr>
<tr>
<td></td>
<td>Tiel continuous, Holland peat continuous generally but thickness varies, Gorkum unit not continuous, in the form of lens, intercalated, Basal peat not continuous either, and merged with Holland peat locally, Pleistocene commonly continuous</td>
</tr>
<tr>
<td><strong>Geol. Process</strong></td>
<td>More than 2 sedimentological cycles between fluvial and marine deposition</td>
</tr>
<tr>
<td><strong>Model Selection</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Geo. Complex</strong></td>
<td>Simple, fairly complicated</td>
</tr>
<tr>
<td><strong>Sampling dens.</strong></td>
<td>50 m * 50 m - 100 m * 100 m</td>
</tr>
<tr>
<td><strong>Resolution (x, y)</strong></td>
<td>50 * 50, 25 * 25, 12.5 * 12.5 m</td>
</tr>
<tr>
<td><strong>Resolution (Z)</strong></td>
<td>1,0,5,0.25</td>
</tr>
<tr>
<td><strong>Algorithm</strong></td>
<td>Inverse Distance (D) (power =2)</td>
</tr>
<tr>
<td><strong>Likelihood</strong></td>
<td>Very/moderate</td>
</tr>
<tr>
<td></td>
<td>Moderate</td>
</tr>
<tr>
<td></td>
<td>Moderate/very</td>
</tr>
<tr>
<td></td>
<td>Most</td>
</tr>
<tr>
<td><strong>Scale</strong></td>
<td>3-4</td>
</tr>
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<td></td>
<td>3-4</td>
</tr>
<tr>
<td></td>
<td>2-3</td>
</tr>
<tr>
<td></td>
<td>2</td>
</tr>
<tr>
<td><strong>Application</strong></td>
<td>Regional</td>
</tr>
<tr>
<td></td>
<td>Semi-regional</td>
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<tr>
<td></td>
<td>Semi-Specific</td>
</tr>
<tr>
<td></td>
<td>Specific</td>
</tr>
</tbody>
</table>
7.1.6 Limitation for index rating

If the quality of data collected from surface natural outcrops or from excavated exposed surfaces is considered, the time and exact location of the observation can be important. Therefore, it is prudent to determine the distribution in space and time of the feature observed, and record exact location and time at which the observation has been made.

Interpretations of complex geological conditions from limited information are very difficult to obtain manually on paper or with the assistance of computers. However, complex 3D geological interpretation on a computer generally results in more geologically consistent results. This may require substantial interpretative input. The rating values given for each element should be based on knowledge reasoning and judgement. Although fair judgment is done by the expert, there is no full guarantee for the final result assessed based on the likelihood index values because evaluation of subsurface geo-objects geometry or property as stationary in their original position or mobile for their direction of movement cannot be verified fully by the conventional theory or hypothetical reasoning, but may be within a limit of an acceptable range with an error, in the order of a few meters in any direction (horizontal or vertical).

7.1.7 Importance of assessment of the likelihood of models

Risk assessment methods are used in developed countries, particularly in the insurance and manufacturing industries. However, human-related risks need assessment with a high degree of accuracy so there is a need to refine and develop methods of risk assessment to the generation of models that are applicable in natural geo-hazards in the planning and environments monitoring affairs. Like the Reeuwijk area such techniques will have value in planning development, civil engineering construction and for the insurance industry. Forecasting the probable hazard to occur in certain parts of a project (area of interest) before, during and after implementation demand reliable subsurface information to evaluate hazard and risk in due course of time (social, environmental).

In the process of subsurface solid modelling, there could be a direct impact of the poor quality modelling approach of the subsurface either as a result of ignorance of some information or bias due to some anomalous results encountered during interpreting the data and lack of experience in handling multiple data set and organizing in a logical scientific way to represent the real world. The degree of its accuracy determines success of the particular project and in turn implies a positive impact on social and economic issues. Whether or not the risks can be avoided, is important to estimate their severity by a Risk Analysis. The degree of risk is the expected impact of damage; loss, or harm from a given hazard under particular circumstances. Whether the hazards can be translated into risk depends on a number of factors Based on formula by Clayton (2001):

\[
\text{Degree of Risk (R)} = \text{Likelihood (L)} \times \text{Effect (E)}
\]

Risk results from the combination of a hazard and the vulnerability of the structure or activity for the hazard. Even although it is often possible to assess the likely loss, the importance of any given risk depends on the risk tolerance of the company or institution or person taking the risk. For example to a
small contractor the loss of a few thousand euros will be extremely serious, while for a major company this might be insignificant. In general, risk tolerance depends on each individual or, organization within the context of the society. It is necessary to establish a scale of risk for each company, for each major type of risk (financial, health and safety, environmental) and sometimes for individual projects. Based on the combination of existing information, experience and expert opinions, the type of hazard and its severity can be identified, however, the effect can also be tentatively estimated without knowing the level of risk. For simplicity, it is possible to fix the risk level and then to estimate the effect based on different levels of likelihood of models. For example, if the degree of risk is fixed to (5%) as accepted, then the effect can be estimated by:

\[
\text{Effect} = \frac{\text{Degree of Risk}}{\text{Likelihood}}
\]

Applied to subsurface modelling a high level of likelihood of a model will give least effect in term of increased cost or time. The risk is a function of geological conditions, economic, societal, and technological uncertainties.

7.2 Conclusions and Discussions

Conclusions and discussions on the assessment of the likelihood of models are summarized as follows:

7.2.1 Conclusions

1) The assessment of the constructed models can be realized by the visual inspection of the 2D section and fence diagrams in aspects of the boundary variations of units and their spatial associations of different geological units. The re-interpretation is conducted whenever doubt exists as to differences in stratigraphic sequences until a reasonable model is achieved.

2) The comparison of constructed models is also possible by comparing the thickness and volume of the individual unit.

3) In this study, the conceptual likelihood model assessment approach is proposed for ranking the constructed models. It consists of several steps to execute ranking models. First, three basic parameters affecting the reliability of subsurface 3D model are summarized, i.e., data quality, interpretation quality and the selection of the modelling algorithm. Then elements for each kind of parameter are assigned to a subjective weighting based on the professional practice and the background information. Finally the likelihood assessment index matrix can be reasoned for ranking the resulting model.

7.2.2 Discussions

1) As it has been discussed previously, ranking the likelihood of models involves several stages. Due to the limited research time, it is not possible to complete the whole assessment system, only the conceptual likelihood assessment framework is proposed in this work, further work needs to be done in the future.
2) The weighting factor mentioned in each element within three basic quality parameters is based on professional practice and background information of the test area, however it can be supplemented any time after collecting and analyzing the broad views from the 3D geoscientific modelling expertise, hence, this approach can be applied in other areas.

3) In this study, the multiple models are built based on available information and plausible scenarios of the interpretation of the borehole data. Considering the specific situation of the Dutch geological settings, the CPT data interpretation is very useful for assessing the interpretation of the geological units as well as the geotechnical units. Therefore, the incorporation of CPT data interpretation will further improve the constructed models in this study.
8 Conclusions and Recommendations

8.1 Conclusions

The objective of the research is to build multi 3D models based on a geo-knowledge reasoning framework and evaluate factors affecting the reliability of sub-surface geological and geotechnical models. The conceptual likelihood model assessment approach is proposed. The case study is conducted on the Reeuwijk borehole data. The conclusions can be drawn as follows:

1) The data of 63 boreholes are selected for constructing the multi lithological and stratigraphic models. For the geotechnical property modelling, the values of the average dry and saturated unit weights of units are used based on the Dutch soil classifications standard (NEN 6740).

2) The borehole data represent a limited subsurface volume; the space between boreholes is an interpolated element that is always a point of discussion. However, through the integration of the qualitative judgment by the geo-reasoning framework, reliable models can be achieved.

3) Four conceptual models have been constructed based on available information and the interpretation of the borehole data based on geo-knowledge reasoning framework. From Model 1 to Model 4, it reflects the increased complexity and specific information from the very simple general situation to complex situation. The multi models for each conceptual model are generated based on different grid sizes (model resolution), different proportion of the borehole data used in the interpretation, and different modelling algorithms.

4) To evaluate spatial variation of units, three degrees modelling resolution are used in the modelling processes. Units originating in a marine environment show more consistent layers than those originating in a fluvial or lacustrine environment. As the modelling resolution becomes large or the grid cells are smaller, features or layers of small patches are more clearly separated.

5) The comparison of the constructed models has been conducted based on the visual inspection in 2D/3D views and the comparing of the statistical parameters, such as the thickness and volume of units. The models obtained from omitting 10% of the number of borehole have shown nearly the same result with the model built from 100% borehole numbers.

6) The reliability of models is associated with uncertainty in the process of data quality, interpretation quality and the selection of modelling algorithms. The conceptual likelihood model assessment framework is proposed for ranking the generated models.
7) Reliability of models is assessed depending on the purpose of the modelling process, for example, from the site investigation point of view, model 4 gives a better result, because the detailed information is presented, whereas, the conceptual model 1 represents a regional overview of the unit boundary, i.e., between the Holocene and Pleistocene stratigraphy. The ranking result shows that the lithostratigraphic model IV_100C (100% borehole data with modelling resolution of 12.5 x 12.5 x 0.25 m) is considered to be more reliable for representing the subsurface units when compared with the existing reference section and the background information.

8) In this study, all of the modelling work is conducted in Rockworks 2002. The software is easy and flexible to use, especially for modelling the sedimentary units. However, there are limitations with this software, for example in the lithology-modelling mode, only the horizontal blending algorithm can be chosen. In the stratigraphy mode, the repetition of the geological units is not allowed in the interpretation database.

9) Due to uncertainties in data acquisition, data interpretation and modelling processes, the level of reliability of the constructed models differs from person to person involved in the modelling because of different levels of experience, education and expertise. Therefore, the subsurface model can never be absolutely accurate and representing completely the reality even when the multiple sources of data are available and the modelling is done by the experienced geologist and engineer. Therefore, the minimum level of acceptability for the ultimate model should be set for each specific project.

8.2 Recommendations

The main recommendations that can be made are as follows:

1) Though many possibilities exist to reconstruct subsurface models in an attempt to represent the geo-object and its properties based on interpretation of point data through observation and measurements of the system, the material properties vary in vertical and horizontal dimensions and often also in time. For complete understanding of the subsurface geo-object, the role of groundwater should be considered for any subsurface modelling.

2) For the validation of the result, extra geotechnical data such as CPT data are required.

3) Future work should define the proposed likelihood assessment approach in a suitable mathematical computation, such as fuzzy logic, and then, the assessment of the reliability of models can be expressed in terms of probability.
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Appendices

Appendix I: Original Boreholes Database used in this study (Dutch version)
Appendix II: Geological section along profile H-H' oriented NNW-SSE; (Source: the geological map of Holland, sections sheet3, Gorinchem West (38W))

Appendix III: Multi conceptual Models

Appendix III-1: Conceptual model I based on data sizes 90%, and 50%
Appendix III-2: Conceptual model II based on data sizes 90%, and 50%
Appendix III-3: Conceptual model III based on data sizes 90%, and 50%
Appendix III-4: Conceptual model IV based on data sizes 90%, and 50%

Appendix IV: Table presenting volume of the geological units of different resolutions, and data size
Appendix IV-1: volume of geological units in conceptual model I
Appendix IV-2: volume of geological units in conceptual model II
Appendix IV-3: volume of geological units in conceptual model III
Appendix IV-4: volume of geological units in conceptual model IV

Appendix V: Histogram presenting volume comparison of litho units based on different data size
Appendix V-1: Volume comparison of litho units, of 50%, 90%, 100% size and different resolution
Appendix V-2: Comparisons of conceptual Models II, III, & IV data sizes 50%, 90%, and 100%
Appendix V-3: Comparisons of conceptual Models I, II & III, data sizes 50%, 90%, and 100%

Appendix VI: Lithostratigraphic and chro stratigraphic section of multi models
Appendix VI-1: Chro stratigraphic section of the constructed models with variable data size and resolutions along NNW-SSE
Appendix VI-2: Lithostratigraphic section of the constructed models with variable data size and resolutions along NNW-SSE

Appendix VII: Geotechnical property multi models and sections
Appendix VII-1: Appendix VII-1: Geotechnical property models (saturated & dry unit weight) of units based on 100% and 90% data size respectively.
Appendix VII-2: Vertical profiles of the property models, along NNW-SSE section on different data size and modelling resolutions
Appendix I: Original Borehole Database used in this study (Dutch version)

<table>
<thead>
<tr>
<th>HoleID</th>
<th>East</th>
<th>North</th>
<th>Level</th>
<th>Depth From</th>
<th>Depth To</th>
<th>Lithology</th>
<th>Dutch litho description</th>
</tr>
</thead>
<tbody>
<tr>
<td>452-114-0005</td>
<td>114575</td>
<td>452910</td>
<td>-1850</td>
<td>6410</td>
<td>0</td>
<td>K</td>
<td>[KLEI,<em><strong>,</strong>**,</em>] humeus</td>
</tr>
<tr>
<td>452-114-0005</td>
<td>114575</td>
<td>452910</td>
<td>-1850</td>
<td>6410</td>
<td>400</td>
<td>V</td>
<td>[VEEN,<em><strong>,</strong>**,</em>] bosveen</td>
</tr>
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<td>452910</td>
<td>-1850</td>
<td>6410</td>
<td>2600</td>
<td>K</td>
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<tr>
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<td>452910</td>
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<td>6410</td>
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<td>[VEEN,<em><strong>,</strong>**,</em>] MONO</td>
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<td>452905</td>
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<td>[VEEN,<em><strong>,</strong>**,</em>] bosveen</td>
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<td>[BODEM,<em><strong>,</strong>**,</em>] zwart zandigE</td>
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Appendix II: Geological section along profile H-H' oriented NNW-SSE; (Source: the geological map of Holland, sections sheet3, Gorinchem 38 West)

Legend

- **Ti**: Tiel deposits: Flood basin deposits (clay)
- **Hvb**: Holland peat: wood
- **Hva**: Holland peat: phragmites peat
- **G0**: Gorkum: channel deposits (sand) and levee deposits (sandy clay)
- **Tw3**: Twente Fm: Eolian deposits (cover sands)
- **Kr**: Kreftenheye Fm: Fluvial deposits: gravely sand
Appendix III: Multi conceptual Models

Appendix III-1: Conceptual model I based on 90%, and 50% of borehole numbers used

Appendix III-2: Conceptual model II based on 90%, and 50% of borehole numbers used

Appendix III-3: Conceptual model III based on 90%, and 50% of borehole numbers used

Appendix III-4: Conceptual model IV based on 90%, and 50% of borehole numbers used
Appendix III-1 Conceptual model I based on data sizes of 90%, and 50% borehole numbers used

Solid geology models based on conceptual Model I using ID algorithms, Model1 on different grid sizes, Model1_90A (50 x 50 x 1m), Model1_90B (25 x 25 x 0.5 m), Model1_90C (12.5 x 12.5 x 0.25m), Vertical exaggeration 100 x, Southwest view

Solid geology models based on conceptual Model I using ID algorithms, Model1 on different grid sizes, Model1_50A (50 x 50 x 1m), Model1_50B (25 x 25 x 0.5 m), Model1_50C (12.5 x 12.5 x 0.25m), Vertical exaggeration 100 x, Southwest view

Appendix III-2: Conceptual model II based on data sizes 90%, and 50%
Solid geology models based on conceptual Model II using ID algorithms,
Model2 on different grid sizes, Model2_90A (50 x 50 x 1 m), Model2_90B (25 x 25 x 0.5 m), Model2_90C (12.5 x 12.5 x 0.25 m), Vertical exaggeration 100 x, Southwest view.

Solid geology models based on conceptual Model II using ID algorithms,
Model2 on different grid sizes, Model2_50A (50 x 50 x 1 m), Model2_50B (25 x 25 x 0.5 m), Model2_50C (12.5 x 12.5 x 0.25 m), Vertical exaggeration 100 x, Southwest view.

Conceptual model III based on 90% and 50% of borehole numbers used.
Solid geology models based on conceptual Model II using ID algorithms, Model3 on different grid sizes, Model3_90A (50 x 50 x 1m), Model3_90B (25 x 25 x 0.5 m), Model3_90C (12.5 x 12.5 x 0.25m), Vertical exaggeration 100 x, Southwest view.

Solid geology models based on conceptual Model II using ID algorithms, Model3 on different grid sizes, Model3_50A (50 x 50 x 1m), Model3_50B (25 x 25 x 0.5 m), Model3_50C (12.5 x 12.5 x 0.25m), Vertical exaggeration 100 x, Southwest view.

Conceptual model IV based on 90%, and 50% of borehole numbers used.
Solid geology models based on conceptual Model IV using ID algorithms:

Solid mod4_90 with different grid size, model4_90A (50x50x1), model4_90B (25x25x0.5) and model4_90C (12.5x12.5 x0.25) vertical exaggeration of 100 x viewed from above southwest.

Solid geology models based on conceptual Model II using ID algorithms:

Solid mod4_50 with different grid size; model4_50A (50x50x1), model4_50B (25x25x0.5) and model4_50C (12.5x12.5 x0.25) vertical exaggeration of 100 x viewed from above southwest, Model constructed from 50% of the data.
Appendix IV: Volumes of the geological units of different resolutions, and data size (Cu. m)

Appendix IV-1: volume of geological units in conceptual model I

Appendix IV-2: volume of geological units in conceptual model II

Appendix IV-3: volume of geological units in conceptual model III

Appendix IV-3: volume of geological units in conceptual model IV
Appendix IV-1: volume (m$^3$) of geological units in conceptual model I

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Appendix IV-2: volume of geological units in conceptual model II

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Appendix IV-3: volume of geological units in conceptual model III

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Appendix IV-3: volume of geological units in conceptual model IV

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Appendix V: Volume comparisons of units based on different proportion of boreholes numbers used and resolutions

Appendix V-1: Volume comparisons of units in litho models with 50%, 90%, 100% of borehole numbers used and different resolutions

Appendix V-2: Volume comparisons of models based on the conceptual model II, III & IV with 50%, 90%, 100% of borehole numbers used

Appendix V-3: Volume comparisons of conceptual Models I, II III, data sizes 50%, 90%, and 100% of borehole numbers used
Appendix V-1: Volume comparisons of units in different litho models with 50%, 90%, 100% of borehole numbers used and different resolutions

### Volume comparison (Grid size)

**Model 50A**
- K: 133 12 500
- V: 132 22 500
- Z: 390 75 000

**Model 50B**
- K: 114 96 563
- V: 139 86 250
- Z: 413 28 125

**Model 50C**
- K: 108 40 117
- V: 147 12 099
- Z: 365 41 797

### Volume comparison (Grid size)

**Model 90A**
- K: 122 30 000
- V: 144 45 000
- Z: 376 75 000

**Model 90B**
- K: 104 37 187.5
- V: 152 42 187.5
- Z: 393 62 50

**Model 90C**
- K: 100 76 953.1
- V: 150 03 320.3
- Z: 412 61 328

### Litho_unit volume comparison (Grid size)

**Model 100A**
- K: 126 65 000
- V: 139 42 500
- Z: 383 50 000

**Model 100B**
- K: 107 42 187.5
- V: 148 17 187.5
- Z: 405 62 50

**Model 100C**
- K: 103 14 140.6
- V: 146 83 632.8
- Z: 420 86 328
Appendix V-2: Volume Comparisons of Conceptual Models II, III, IV with 50%, 90%, and 100% of borehole numbers used

### Comparison of Models

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### Comparison of Models (data size)

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### Comparison of Models (variable data size)

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Appendix V-3: Volume Comparisons of units of conceptual Models I, II, III, with 50%, 90%, and 100% of borehole numbers used.
Appendix VI: Chrono stratigraphic and Lithostratigraphic section of conceptual model IV

Appendix VI: I Chrono stratigraphic section of the constructed models with variable data size and resolutions along NNW-SSE

Appendix VI:II Lithostratigraphic section of the constructed models with variable data size and resolutions along NNW-SSE
Appendix VI-1: Chro stratigraphic section of the constructed models with variable data size and resolutions along NNW-SSE
Appendix VI-2: Lithostratigraphic section of the constructed models with variable borehole numbers used and resolutions along NNW-SSE.
Appendix VII: Geotechnical property multi models and sections

Appendix VII-1: Geotechnical property models (saturated & dry unit weight) of units based on 100% and 90% of borehole numbers used respectively.

Appendix VII-2: Vertical profiles of the property models (dry unit weight) along NNW-SSE section on variable borehole numbers and modelling resolutions
Appendix VII-1: Geotechnical property models (saturated & dry unit weight) of units based on 100% and 90% of borehole numbers used respectively.

Appendix VII-2: Vertical profiles of the property models (dry unit weight) along NNW-SSE section on different borehole numbers used and modelling resolutions