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Three and more dimensional modelling in geo-engineering

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Abstract Full three-dimensional modelling has been developed and is implemented for many sites where engineering structures are built. Such computer models of the subsurface allow for a more sophisticated handling of subsurface data leading to, for example, better dimensioning of geotechnical units, the evaluation of hazard and risk, foundation design, tunnel routing, planning and building, etc. Other applications are the back-analysis for completed civil engineering projects to verify the correctness of assumed and estimated ground models and parameters, the verification of the correctness of constitutive models for ground behaviour and the use of back analysis to improve building methodologies or equipment. The paper illustrates some of these advantages with a number of state-of-the-art applications of three-dimensional modelling in engineering geology and geotechnical engineering, highlighting a number of key issues when computer-aided 3D modelling is used: the definition of geotechnical (homogeneous) zones, scale and detail, uncertainty and likelihood of the developed model.

Keywords 3D modelling · Engineering geology · Geotechnics · Likelihood

Résumé La modélisation tri-dimensionnelle est aujourd'hui classique et est mise en œuvre pour de nombreux projets d'ingénierie. De tels modèles numériques relatifs aux conditions de sub-surface permettent une utilisation plus précise de données conduisant par exemple à la définition d'unités géotechniques, à l'évaluation des aléas et risques, au dimensionnement de fondations, au tracé de tunnels, à la construction et l'aménagement en général. D'autres applications sont relatives à des rétro-analyses de projets de génie civil terminés pour vérifier la justesse de modèles de terrain et des paramètres associés, l'adéquation de modèle de comportement mécanique des matériaux et pour en conséquence améliorer les méthodologies de construction. L'article illustre quelques unes de ces conclusions, avec plusieurs applications relatives à l'état de l'art en la matière, mettant en évidence l'apport des techniques de modélisation tri-dimensionnelles dans le domaine de la géologie de l'ingénieur et la géotechnique, soulignant quelques points clés dans la mise en œuvre de la modélisation 3D assistée par ordinateur : la définition d'unités géotechniques, les problèmes d'échelle et de précision, les problèmes d'incertitude et de vraisemblance des modèles développés.

Mots clés Modélisation 3D · Projets d'ingénierie · Géologie de l'ingénieur

Introduction

Modelling the subsurface is required for the design of foundations of buildings, bridges, tunnels, underground parking/garages, etc. In urban planning, modelling the subsurface in three-dimensions is not yet commonly used. However, the increasing pressure for the use of the surface and subsurface of the earth requires an optimum use of the subsurface space and 3D modelling will become more and more common to achieve this.

In engineering geological and geotechnical studies it is normal to make a 3D model of the distribution of the geotechnical properties of the sub-surface (for example see Fig. 1). Such a model consists of a boundary model that gives the boundaries between the different defined geotechnical units and a property model for the distribution of the geotechnical properties within the geotechnical units. In principle the model has to be 3D and able to represent changes of geotechnical properties over time, i.e. the model should be 4D with time as the fourth dimension.

Dedicated computer programs for modelling of the subsurface were developed originally in the mineral exploration, mining and oil and gas industries. The mining industry focussed on spatial modelling of geology and ore bodies, generally based on large quantities of borehole data. The oil industry focussed on modelling the geology and oil/gas reservoirs, based on limited borehole data but detailed exploration seismic data (Hack and Sides 1994; Loudon 2000; Houlding 1994; Turner 1992).

The first versions of 3D programs ran on mainframe computers and were generally very cumbersome to operate. Later these programs were converted to be used on PC's and became more user-friendly. A next step in the development occurred when the PC became widely available. Many engineers and geo-scientists started to make their own subsurface modelling programs in, for example, spreadsheets. Most programs were 2D; later some extended to three dimensions and many incorporated time as a factor in specially developed relations between spreadsheet cells; hence effectively numerical 2D and 3D programs were developed (Bonham-Carter 1994; Orlic 1997; Rosenbaum and Turner 2003).

In engineering geology and geotechnical engineering the first efforts to use computer aided modelling started with programs originally developed in the mining industry, sometimes adapted to the particular requirements of engineering geology (e.g. Lynx GMS) (Houlding 1994; Orlic 1997; Orlic and Hack 1994).

Some 10 years ago this development was in full swing and the expectation was that computer based modelling of the subsurface would soon be standard practice in engineering geology and geotechnical engineering. However, as discussed below, this development was not as fast as had been anticipated.

Introduction of 3D modelling programs in geo-engineering design practice

During the past decade the development and increasing use of computer based modelling for geo-engineering purposes seemed to stall. Full 3D programs are now sometimes used for modelling the subsurface for very large projects, but more often they are just 2.5D, i.e. a layer boundary model is made in which the properties per layer are kept constant. In even more projects only a 2D programs is used to make horizontal and vertical sections or no computer programs are used at all and just the old fashioned but trusted paper method for the preparation of subsurface models and sections.

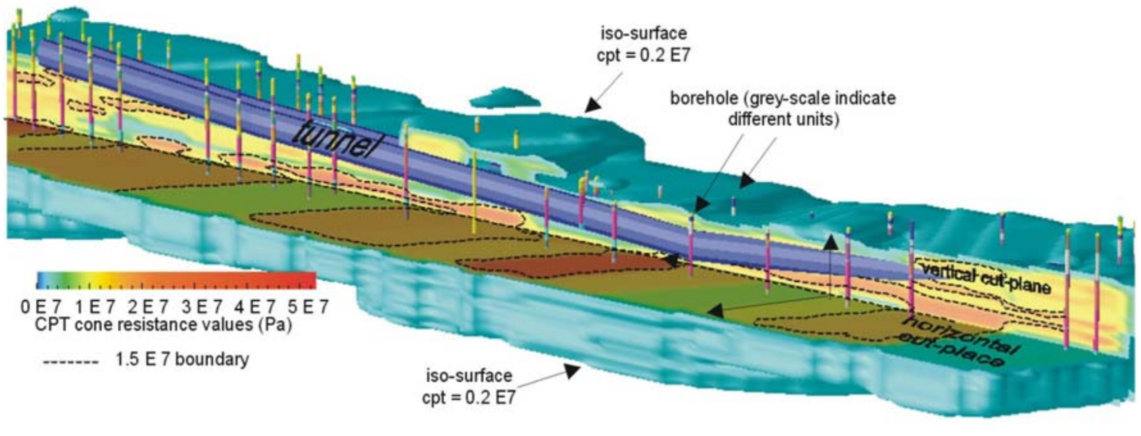


Fig. 1 Example of 3D-GIS visualization of proposed tunnel alignment in a solid volume model of the distribution of CPT cone resistance values, with boreholes showing geotechnical units and two cut-planes to show the distribution of CPT values (Heinenoord Tunnel, Netherlands; after Ozmutlu and Hack 2002)

What are the reasons why the introduction of computer-aided modelling in the geo-engineering design practice is so slow? The following observations can be made.

- The amount and detail of subsurface data in most geo-engineering projects is usually very limited and therefore the added value of using a digital 3D system is not justified against the increase in costs of the project due to the computer modelling; moreover extensive use has to be made of expert knowledge during the modelling.
- Not all required tasks are usually combined in one program and the market is used to applying sophisticated existing computer (numerical and analytical) calculation programs for special tasks.

Limited amount of data and use of expert knowledge

The amount of data on the subsurface available in civil engineering projects is normally very limited. Some crude geological map information (generally from a map on a far larger scale than the project) together with a couple of boreholes and soundings, sometimes supplemented by geophysical data, is generally all that is available for the modelling of the subsurface in civil engineering projects. To create a model of the subsurface from this limited amount of data requires the person making the model to have a large amount of expert knowledge (Fedra 1995; Ozmutlu et al. 1998; Ozmutlu and Hack 1998, 2003; Toll 1996; Toll and Barr 2001). The existing programs for modelling the subsurface provide very little or no assistance in this. In addition, making a decent model based on few data in a complicated 3D program is time consuming. It then becomes doubtful whether using a computer program gives an added value. One can mostly far more easily and faster construct the model on paper. The correctness of the model whether on paper or in a program cannot be assessed anyhow, because of the limited amount of data available and the heavy influence of expert knowledge/judgement on the final model. As a consequence, the model on paper will be "just" as good as the digital computer model.

Not all required tasks are usually combined in one program

Three-dimensional modelling programs for the subsurface do not combine all required tasks in one program. In geo-engineering the program should be able to model the geology based on a limited number of boreholes or probing data sometimes supplemented by geophysical data. This is similar to the requirements for subsurface modelling in the oil and gas industry. On the other hand it should be possible in the final subsurface model to use simulations of typical engineering operations such as cutting a slope for a road or making an excavation or a tunnel. These are operations standard in the mining industry but not required in the oil and gas industry. Most commercially available full 3D programs do not or only partially execute both types of operations, simply because their origin is either in the mining or in the oil and gas industry.

The actual calculations of, for example, settlements, deformations, etc. are thus done in dedicated programs that are abundantly available commercially. Many engineers are familiar with these programs and handle them with ease, for example: MPile and MStap (Delft Geosystems 2005), Plaxis (Plaxis 2005), Flac and Udec (Itasca 2005) (an extensive list of special purpose programs is published on http://www.ggsd.com/).

Time as factor in geotechnical processes

Time is at present virtually never a parameter in 3D models of the subsurface. If time is required for the design, for example in a settlement calculation for a foundation, the properties are exported per layer from the modelling program to a dedicated numerical program in which the time-related calculations are executed. Numerical programs model spatial-temporal problems, but are mostly very confined in their application, e.g. the relations between grid cells are generally fully determined by the program and cannot be changed by the user. In addition, time related features, such as creep, weathering, or the process of cementation, are not very well defined. Hence, if time is expected to be important in the design of an engineering structure, the engineer can often only guess how and what the influence will be; the 3D modelling programs do not allow him to model it.

The choice is thus whether to use a highly sophisticated 3D modelling program to model the subsurface and export the data from this model (in a simplified form) to a calculation program, or to make a model of the subsurface based on relatively easily established sections and use this as basis for input in a calculation program. The quality of both subsurface models can neither be compared nor quantified. Hence, whether a lot of time is spent on making a high-quality subsurface model or not will not be reflected in the quality of the result. In a competitive economic environment such as the building industry, it is common to use the easiest, fastest and especially cheapest way, thus to make the model as simple as possible. For computer based modelling of the subsurface to become a normal tool in the building industry the added value should be more obvious or alternatively the use of a computer based modelling program should be simpler and faster. Obviously, it would be best if both conditions could be fulfilled.

Key issues which limit the possibilities of 3D spatial modelling

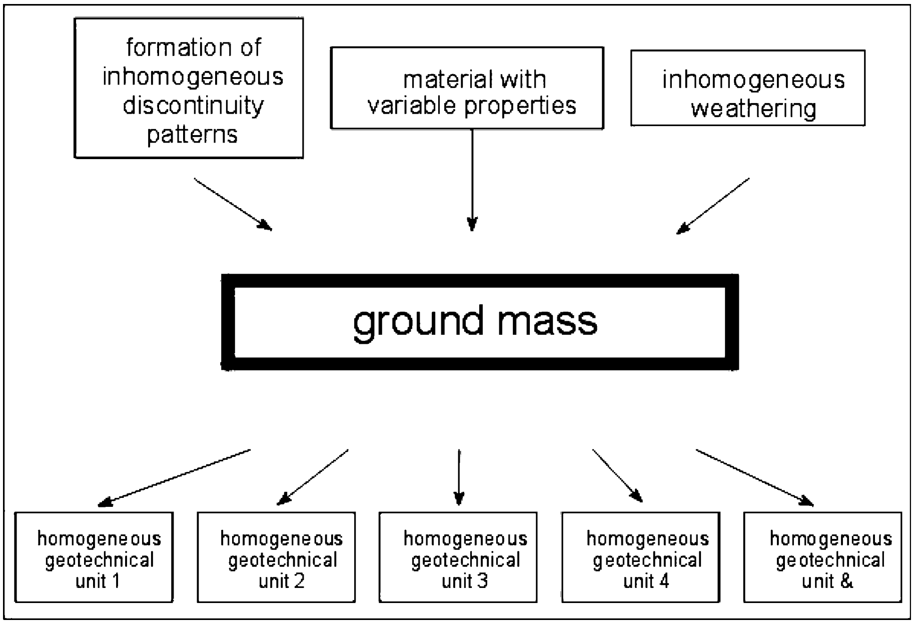
Three-dimensional modelling of the subsurface by computer will only be more widely used when the added value compared to traditional modelling of the subsurface is greater. Options to increase the added value are discussed below.

Geotechnical units

Theoretically, a proper ground description for a geotechnical calculation to determine the behaviour of a soil or rock mass and engineering structure should include all properties in the mass including all spatial variations of these properties. This requirement is unrealistic because this is not possible without disassembling the mass and describing and testing every single piece of ground material. Therefore, a standard procedure is to divide a mass into assumed homogeneous geotechnical units. A geotechnical unit is then, in theory, a part of the mass in which the mechanical properties of the soil or intact rock material are assumed to be uniform. This includes also direction-dependent features such as discontinuities, of which the orientation and properties are uniform within the same geotechnical unit.

Figure 2 shows a schematic visualization of a ground mass and its division in geotechnical units. In practice, homogeneity is seldom found and material and discontinuity properties vary within a selected range of values within every unit. The allowable variation of the properties within one geotechnical unit depends on: (1) the degree of variability of the properties within a mass, and (2) the context in which the geotechnical unit is used. A ground mass with a large variation of properties over small distances necessarily results in geotechnical units with wider variations in properties. The smaller the allowed variability of the properties in a geotechnical unit, the more accurate the geotechnical calculations can be. Smaller variability of the properties of the geotechnical units involves collecting more data, however, and is thus more costly. The higher accuracy obtained for a calculation based on more data, therefore, has 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 allowable variations within a geotechnical unit for the foundation of a highly sensitive engineering structure (for example, a nuclear power station) will be smaller than for a geotechnical unit in a calculation for the foundation of a standard house. No standard rules are available for the division of a mass into geotechnical units and this transformation depends on experience and 'engineering judgment'. However, features such as changes in lithology, faults, shear zones, etc., are often the boundaries of a geotechnical unit. In Fig. 3 a slope is shown in which different geotechnical units are present. The influence of the different geotechnical units on the form of the slope is clearly visible through the changes in slope surface steepness. For more information on this aspect see Hack (1996, 1998), Hack et al. (2003).

Fig. 2 Mass components



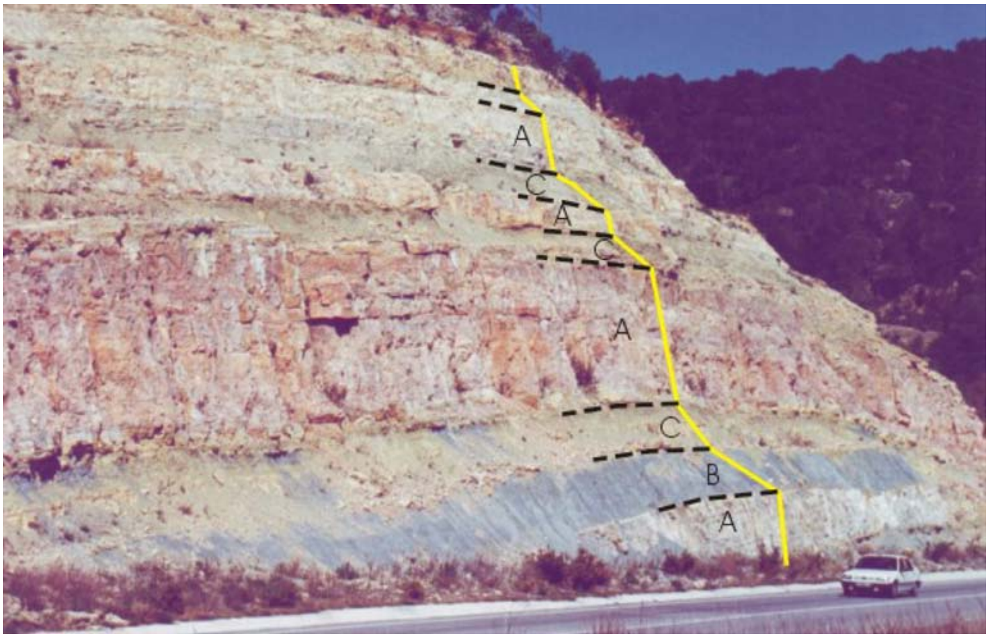


Fig. 3 Different geotechnical units present in a single slope. The units in which a steep slope dip is maintained consist of dolomite and limestone and the units in which a less steep slope dip is maintained consist of calcareous shale

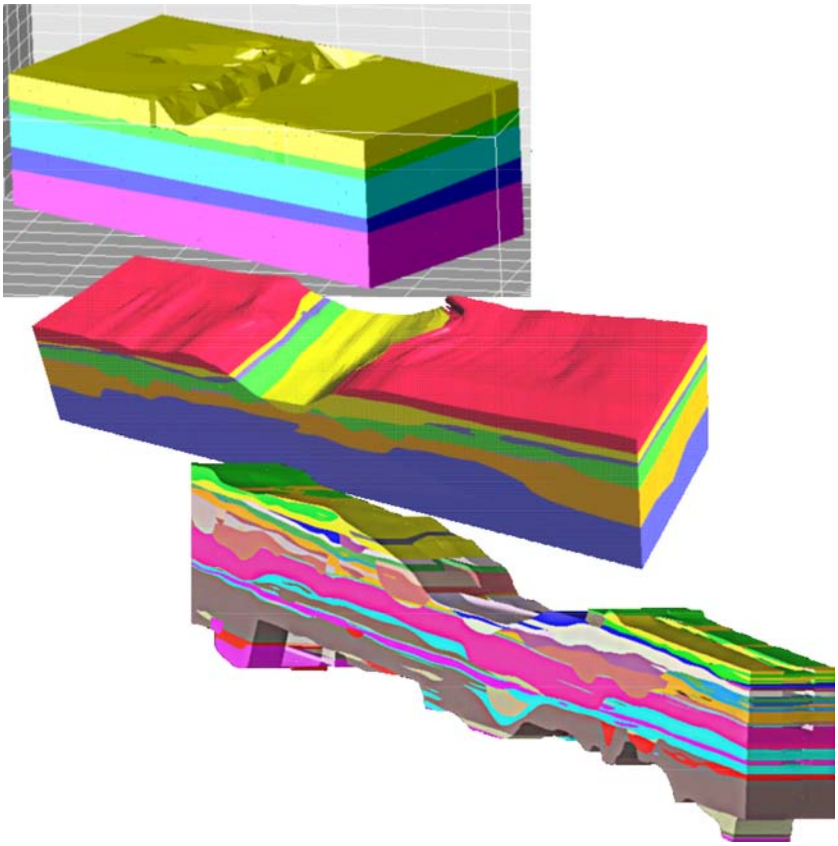


Fig. 4 Subsurface model for the Heinenoord Tunnel, The Netherlands; volume modelled decreases from A to C and detail increases from A to C (after Ozmutlu and Hack 2003)

Scale and detail

The scale on which a model of the subsurface can be made is inherently related to the density and the detail of the data available on the subsurface. Detailed data are generally only available on small areas and on larger areas less detailed data are available (Fig. 4). In a project, the detail of the model is also related to the stage of development of the project; more data become available as the project progresses and hence the models of the subsurface can also become more detailed in the later stages of the project.

Whether the greater detail in such a situation means that the uncertainty of the model decreases does not follow automatically. The complexity of the geology in relation to the complexity of the structure to be built on or in the subsurface determines whether and how the uncertainty is quantified. For this, the modelling aspects influencing the certainty and quality of the model should first be considered.

Uncertainty of the model

In geo-engineering work it is (or should be) common practice to make an estimation of the errors/possible errors in the geotechnical properties of the subsurface and the influence of these errors on the engineering structure to be built in or on it. This is sometimes known as a hazard and risk analysis. Different methodologies, such as "geotechnical base-line methods" (Staveren and Knoeff 2004), probability studies and Monte Carlo simulations (Damsleth and Holden 1994; Hack 1996, 1998; Hack et al. 2003; Srivastava 1994; Viseur and Shtuka 1997), are applied to give a certain amount of quantification of possible errors in the design of an engineering structure due to uncertainty regarding the subsurface properties. However, two very important main points, the geological and geotechnical expert knowledge used to make the subsurface model and the division of the subsurface layers in geotechnical units are addressed in only a very rudimentary way or not addressed at all in these analyses. To understand this it is necessary to go back to the basics of geo-engineering.

Statistical routines exist, in extenso, to calculate the temporal-spatial distribution of properties in a unit. The likelihood of the distribution, or the inherent error in estimating a property at a certain location in space, is well defined if appropriate statistical routines are used (Deutsch and Journal 1998; Houlding 2000). However, much depends on the correctness of the boundaries of the geotechnical units which itself is related to (1) the geology and (2) the variation in properties allowed for each in geotechnical unit.

A geologist, engineering geologist, or a geotechnical engineer normally does the interpretation of the geology. In the interpretation the geologist or engineer makes use of "a priori" knowledge of the geological environment to which the subsurface geology will adhere. The quality of this information, e.g. the "a priori" or expert knowledge that is essential in the interpretation, cannot in general, be quantified at present. If the engineer/geologist is good there will be a good model, or a poor model will result if the engineer/geologist is not so good. The establishment of geotechnical units, as well as the definition of their boundaries and the allowed variation of properties within each unit, depends also on geo-engineering judgment. Generally, it will be based on a balance between improved detail against higher costs. It is clear that no decent analysis of hazard and risk can be made if the quality of the expert knowledge and the definition of the geotechnical units cannot be quantified. Any up-to-date analysis describes wonderfully all sorts of uncertainties in measurable properties, but is totally lacking one of these two main parameters governing, to a large extent, the correctness of the subsurface model.

Example: marine or fluvial

In the western part of the Netherlands most sedimentary layers have either a marine or a fluvial origin. Assume that a foundation has to be made on a sand body in the sub-surface. Some boreholes have been made and all show a sand layer to exist roughly at the required depth. Now the interpretation starts. If the sand layer is of marine origin it can be assumed with reasonable safety that the layer is continuous. However, if the sand layer is of fluvial origin it is very likely to be a lens with a limited lateral extension, and may or may not be continuous between two boreholes. The geo-specialist who knows in which formation the sand layer is situated (i.e. of marine or fluvial origin) will likely make a correct interpretation, while his colleague, who does not know or who starts from the wrong assumption, may produce a completely wrong interpretation—with all the consequences for the foundation and the building resting on it.

The uncertainty in a model is the result of a whole series of different features illustrated in Fig. 5.

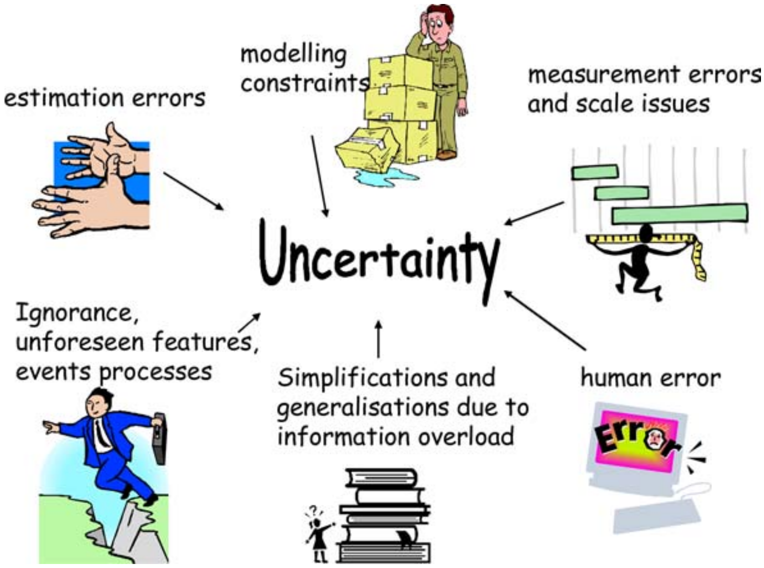
Two case studies with different data densities are given below to illustrate uncertainty in the geological modelling process and the interaction between the model, uncertainty and interpretation.

Case study 1: North Sea seafloor pipeline project

On the bottom of the North Sea, a trench has to be made for a pipeline and the pipeline has to be covered with sand after installation. Hence, the questions for the project are (1) where can a trench be made in sand and (2) where is sand present so that the pipeline can be covered by sand from a nearby location. The data set consists of 340 shallow and deep boreholes in an area of about 15,000 km^2 (134×111 km^2). Problems arise during the 3D subsurface modelling of the geological units, especially with the top of the Holocene sand layer. This is caused by the following facts:

1. The drilling grid is irregular, with most of the holes drilled along the design routing of the pipeline and hence not regularly spaced over the area.

Fig. 5 Causes of uncertainty in a geological model



2. Only a few of the boreholes are deep enough to cover the full depth of the model.
3. No detailed geological information is included in the borehole logs, hence an interpretation based on geological knowledge is difficult.

A part of the pipeline project area is selected for testing the geological modelling process; this area covers 40×26 km^2 with 80 shallow and 2 deep boreholes. The Holocene layer (Dunkirk Formation) is selected as a study unit because of the spatial variation of its materials—silt, peat and sand. Based on the regional geological setting and a detailed analysis of the log data, two simple stratigraphic models are constructed (Fig. 6). In model a the top Holocene layer is further divided into two sub units, whereas in model b only one layer is modelled. The purpose is to investigate the differences between the two resulting models in the thickness and volume of the Holocene unit.

Figure 6 shows a similar geometric image of the spatial distribution of the different geological units in both models a and b. The estimated thickness of the Holocene unit and the estimated volume of it in relation to the total volume are also roughly the same. The

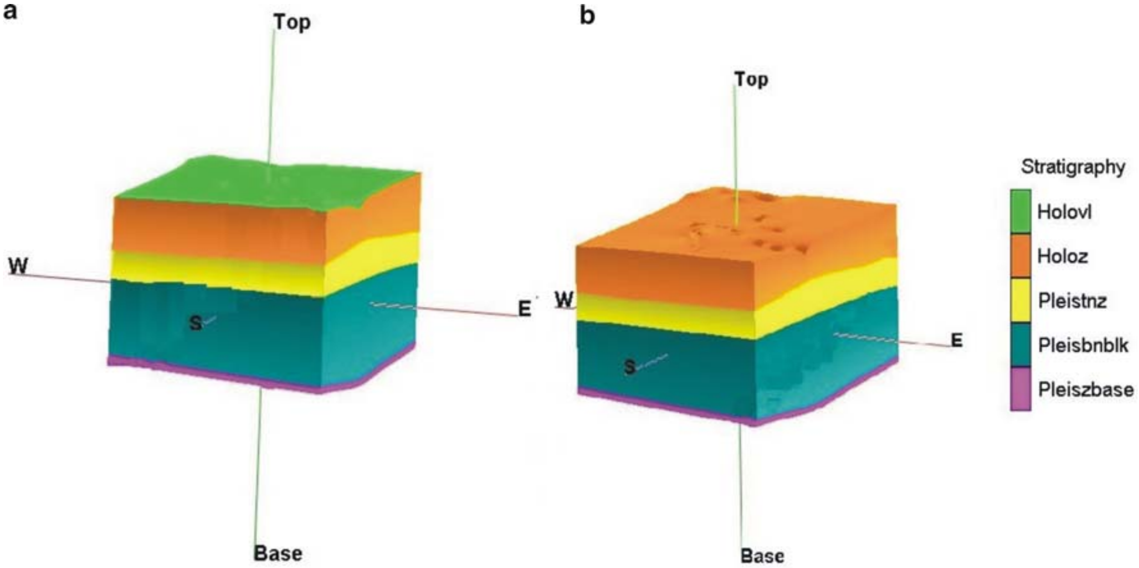


Fig. 6 Two simple stratigraphic models based on the same data. Model a (*left*) incorporates a sub-division of the Holocene in two units; model b (*right*) does not differentiate between units in the Holocene. (vertical exaggeration ×500; model grid size: 500×500×5 m^3)

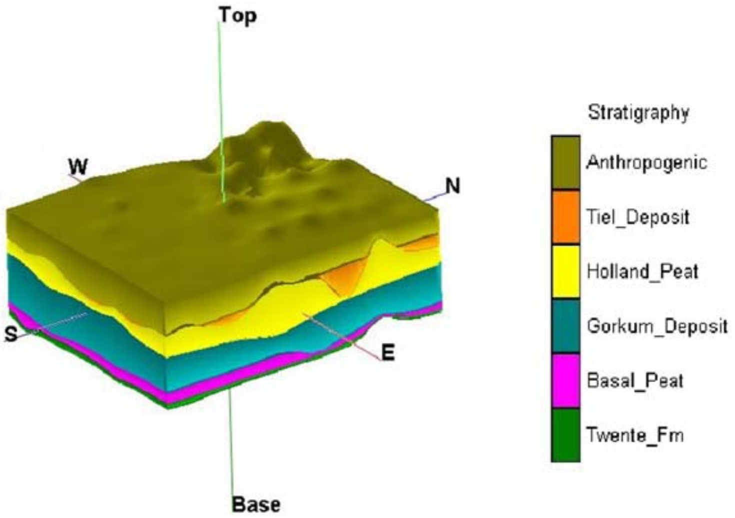


Fig. 7 Three-dimensional subsurface model of the Reeuwijk road project (vertical exaggeration ×100; model grid size: 50×50×1 m^3)

model changes little with additional data and different amount of units and is thus robust for the routing and design of the pipeline. The thickness of the Holocene silt and clay unit that overlies the Holocene sand unit is very thin and variable. The model grid size is, in fact, too large to model these units with sufficient accuracy from this data set which consists of a too small a number of boreholes with too irregular a spacing. Just a limited amount of addition data would add virtually nothing to the quality or reliability of the model. The reliability of the thickness of the Holocene silt and clay could only be improved if considerably more boreholes were undertaken on a smaller grid.

Case study 2: the Reeuwijk Road Project

A subsurface geotechnical model is made to predict settlement of the different soil units due to the changing environmental condition resulting from the loading imposed by a new road to be constructed in the area of Reeuwijk, the Netherlands. The available data are closely spaced and consist of shallow boreholes with detailed logs including geological descriptions and numerous Dutch Cone Penetration Tests (CPTs). Hence, it is assumed that enough data are available for building a high quality geo-database and subsequently a reliable 3D geological and geotechnical model. For this

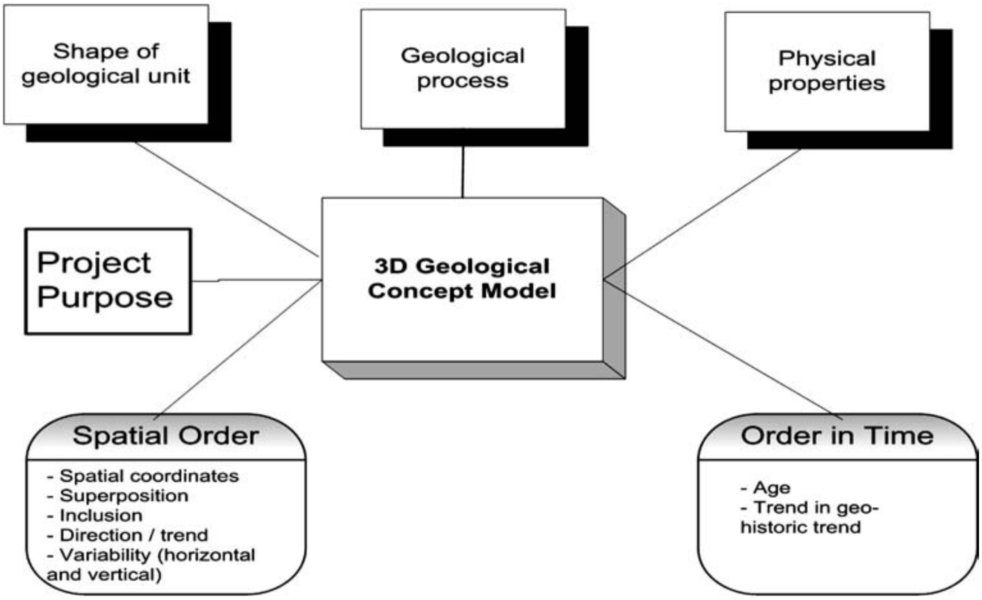


Fig. 8 Expert knowledge in 3D modelling

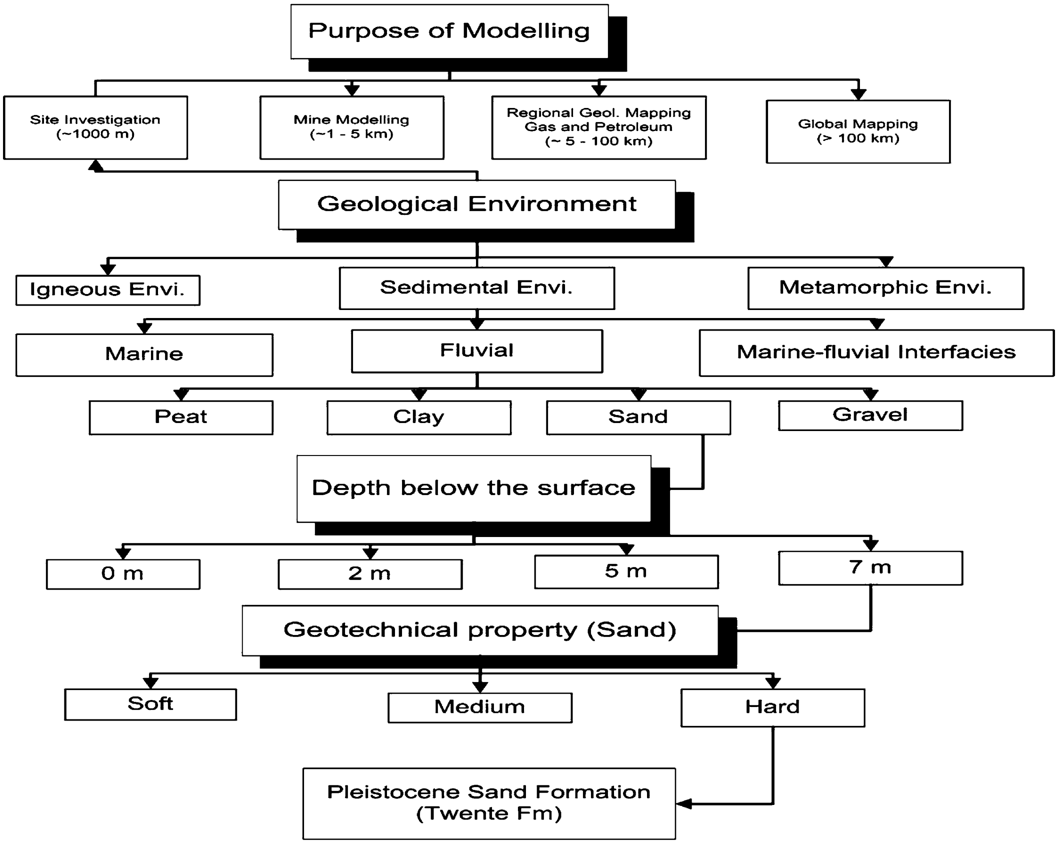


Fig. 9 Likelihood flow scheme interpretation following Fig. 8

example a small area of 3.2 km^2 is selected with 63 shallow boreholes.

The subsurface geological model shown in Fig. 7 is based on the six geological units. The model shows considerable changes if different amounts of units are modelled. The model is therefore not robust for design purposes on a detailed scale.

Modelling based on the likelihood of a model

The Reeuwijk case shows that a straightforward model of the subsurface based on statistics only may not be sufficient even if relatively large quantities of detailed data are available. In the interpretation, an input of expert knowledge is required to obtain a model that is "geologically" justified. However, what is the value of "geologically justified", when the justification is made by one single geologist? Statistically, the reliability of the model could be determined if it was possible to have a representative "bunch" of geologists all doing the same interpretation. Normally, this will not be the case and the interpretation is only that of one or two persons. To be able to determine the reliability of a subsurface model made by only one or two persons a so-called "likelihood interpretation model" is used.

A likelihood model is based on the following three steps:

1. Create a geological knowledge base system for considering the geological information,
2. Integrate the knowledge-based interpretation into a 3D modelling system, and
3. Model the likelihood index based on data quality, interpretation level and model algorithm in relation to the engineering application.

The modelling process then consists of the following two steps: (1) analyse the known data and information (geological, geotechnical, etc.), and (2) build from this a geological knowledge base system for assessing the geological information used for the interpretation. The flowchart for the interpretation of the Pleistocene sand unit (Twente Formation) in the Reeuwijk case is given in Figs. 8 and 9.

This process is applied on the Reeuwijk data set. The results are shown in Fig. 10 for various numbers of units. Reducing the amount of data on which the model is based is used for determining the reliability or

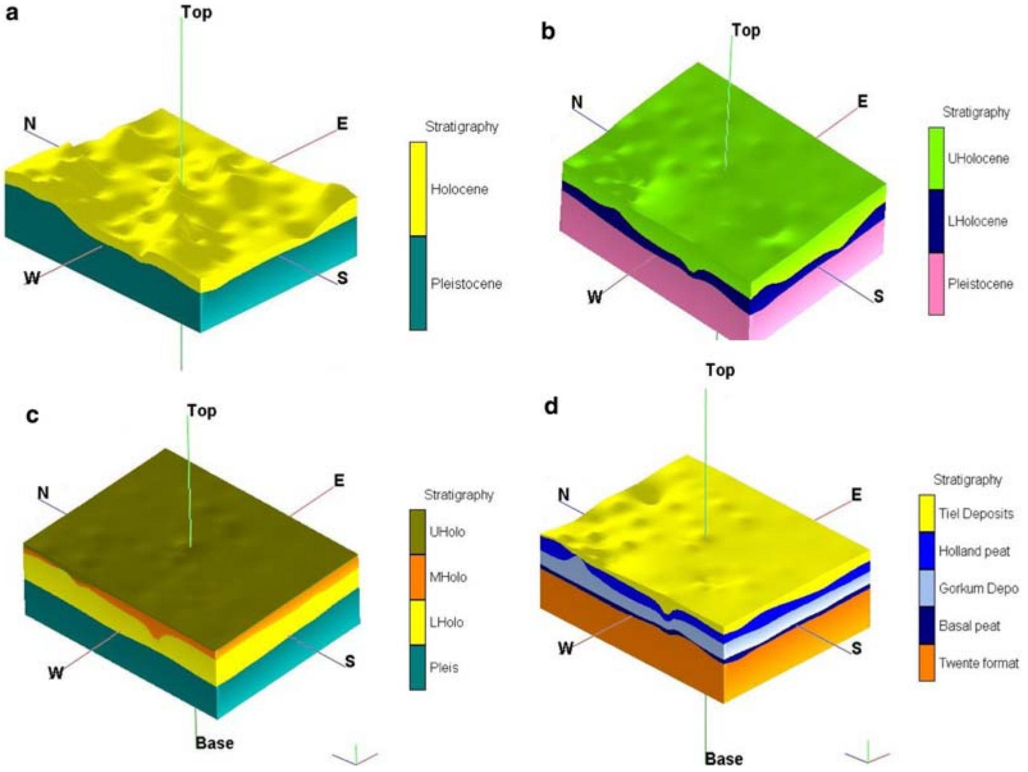


Fig. 10 Result of using flow scheme of Fig. 9; A based on 2 U, B on 3 U, etc

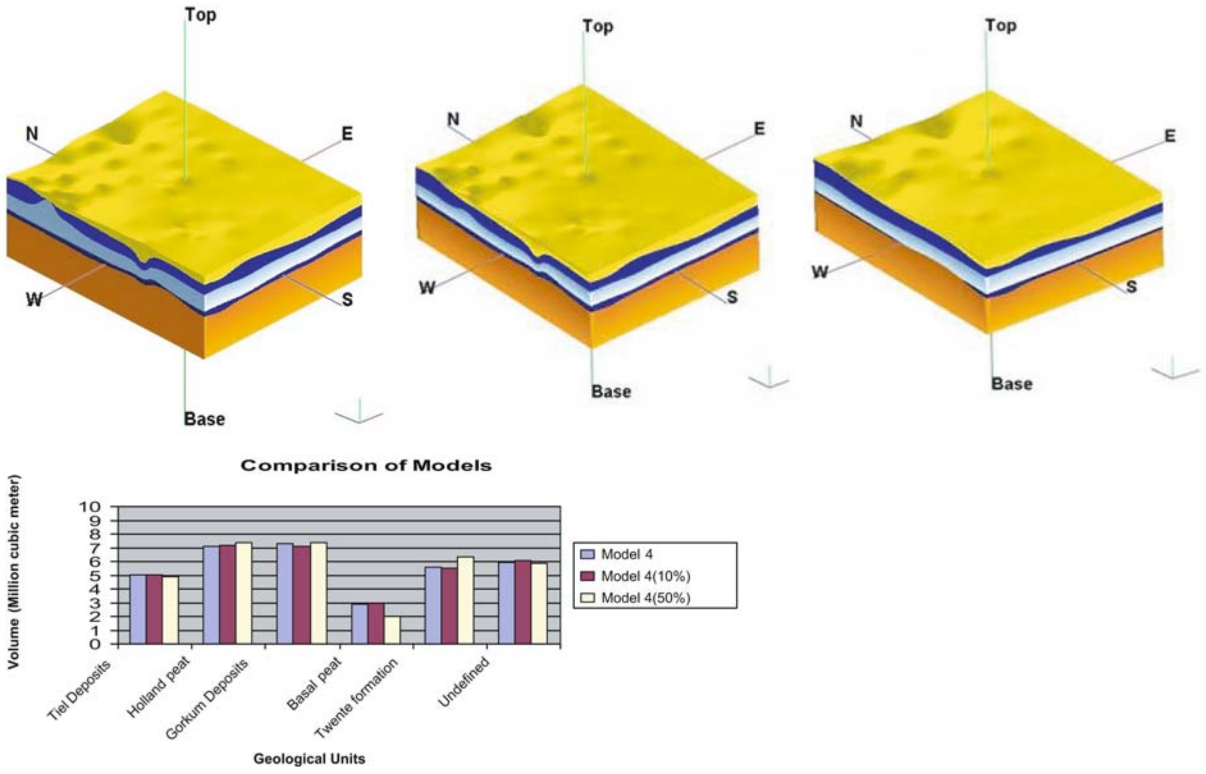


Fig. 11 Three-dimensional model based on various numbers of boreholes; *left* full data set; *middle* omitting 10% of the boreholes; *right* omitting 50% of the boreholes

robustness of the model. In all models, therefore, the amount of data on which the model is based is reduced. If the model changes only little with a reduction of data it is assumed that the original model was robust and thus has the highest likelihood of being the most near reality. The comparison between the different models based on different amounts of data is shown in Fig. 11. This comparison between the different models is based on the volumes of the units modelled. Volumes were used because the settlement on a regional scale depends on the volumes of the settlement sensitive units. Figure 11 shows that model 4 (modelled with 5 U) was the more reliable for the purpose of regional settlement predictions.

Conclusions

Digital modelling of the subsurface is nowadays a well-established technique in many professions that deal with the subsurface. However, in geo-engineering digital modelling of the subsurface is still not fully used. The reasons are various but the main one is that the added value of the benefits is not proportional to the extra work related to using a complicated program. For the future, programs should be more user-friendly, incorporating knowledge base systems that can facilitate the modelling of the subsurface. This will also increase the added value because such systems will allow the determination of the likelihood of the model.

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