HOW FAR WILL UNCERTAINTY OF THE SUBSURFACE LIMIT THE SUSTAINABILITY PLANNING OF THE SUBSURFACE?

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SUSTAINABLE PLANNING

An optimal planning and development of surface and subsurface structures requires that ground properties and the interaction between the ground and the structures to be built are known to position structures in the most optimum position with respect to ground behavior for the full lifetime of the structure. The present situation in the construction process of civil engineering structures is such that, in general, the ground behavior is not used as an input parameter for planning. Information on the behavior of the ground is obtained only just before a structure is going to be built and during construction. The structure is then designed and built based on an assumed ground behavior that is based on ground properties obtained by, for example, boreholes, geophysics or other ground investigation means. Obviously, this methodology prohibits an optimum planning of civil engineering structures in relation to ground behavior. However, even if this methodology could be changed such that information on the ground is available during planning would this information then be of such quality that really an optimum planning could be made?

Ground consists of natural materials, formed and influenced by geological and climate processes over periods of mostly thousands to many millions of years. Inherently variation in ground materials and the subsequent behavior can be large. Secondly, ground materials change in time under influence of, for example, present day climate or groundwater flow. It is impossible to know all variations in space and time exactly. This could only be achieved by excavating the ground completely, which is obviously not a feasible methodology. Alternatively, ground behavior is assumed based on limited information and uncertainty of the behavior is accepted. However, how much uncertainty can be accepted in various stages of planning, design, construction and maintenance of a civil engineering structure?

UNCERTAINTY MODEL

In engineering geology or geotechnical work common practice is (or should be) to make an estimation of the error (or likelihood) of properties in the subsurface and the influence of these errors on the engineering application to be built in or on the sub-surface. The later is also denoted as a hazard and risk analyses for an engineering structure due to uncertainty in geotechnical properties in the sub-surface. Different methodologies, such as "geotechnical base-line methods", probability studies, Monte Carlo simulations, exist to be able to give an amount of quantification of possible errors made in the design of an engineering structure due to uncertainty in sub-surface properties. However, two very important main points are only very rudimentary or not addressed in these analyses. To understand this it is necessary to go back to the basics of engineering geology or geotechnical engineering.

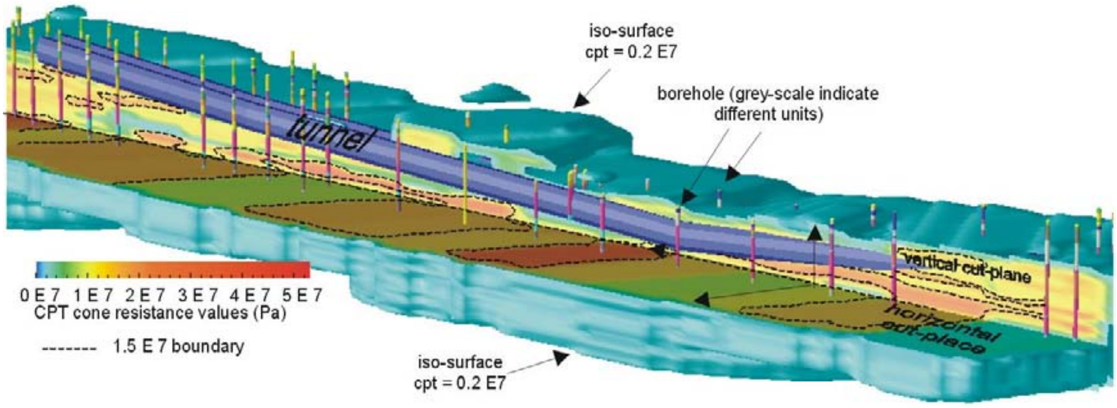

Figure 1 - Example of 3D-GIS visualization of proposed tunnel alignment in a solid volume model of distribution of CPT cone resistance values, with boreholes showing geotechnical units and two cut-planes to show the distribution of CPT values (Heinenoord Tunnel, Netherlands; after Hack et al, 2000)

It should be normal practice to make a three-dimensional model of the geotechnical property distribution of the sub-surface (Figure 1) (Hack, 1999). Such a model consists of a boundary model that gives the boundaries between the different defined geotechnical units (see below) and a property model for the distribution of geotechnical properties in the geotechnical units. In principle the model has to be spatial three-dimensional and be able to represent changes in time of geotechnical properties (e.g. the model should be four-dimensional with time as fourth dimension). Statistical routines exist, in extenso, to calculate the temporal-spatial distribution of properties in a unit. Also the likelihood of the distribution, or better the error made by estimating a property at a certain location in space, is well defined if appropriate statistical routines are used. However, inherit to the likelihood of properties is the correctness of the boundaries of the geotechnical units. This correctness depends on 1) the geology and 2) the variation in properties allowed for each geotechnical unit.

Geological interpretation

The interpretation of the geology is normally done by a geologist, engineering geologist, or a geotechnical engineer. In the interpretation the geologist or engineer makes use of a priori existing knowledge of the geological environments that he or she thinks to be present. The quality of this information that is essential in the interpretation, can, in general, not be quantified at present. If the engineer is good there will be a good model, or a poor model will result if the geologist is not so good. How "good" or how "poor" nobody can quantify. The following example shows this problem. In the western part of the Netherlands 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 (or in the Netherlands Dutch Cone Penetration tests, CPT's) 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 safe be assumed that the layer is laterally 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. A geologist or engineer who makes the correct assumption in which formation the sand layer is situated (e.g. of marine or fluvial origin) will likely make a correct interpretation, while, his colleague who makes the wrong assumption, produces a completely wrong interpretation with all consequences for the foundation and the building resting on it.

Establishment of geotechnical units

The establishment of geotechnical units, as well the boundaries as the allowed variation of properties within each unit, depends on engineering judgment. Generally, it will be based on a balance between improved detail against higher costs.

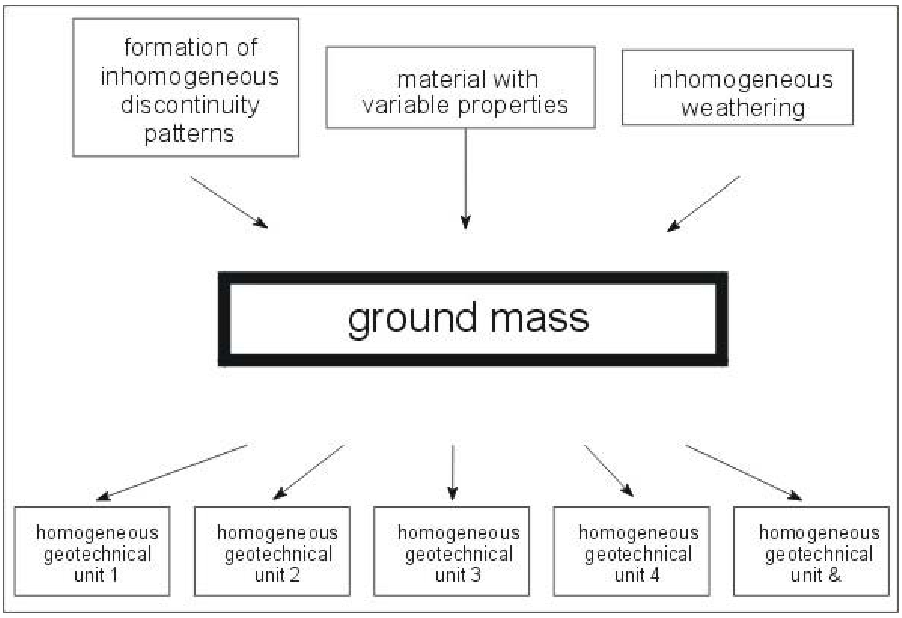

Figure 2 – Ground mass components

Theoretically, a proper description or geotechnical calculation to determine the behavior of a soil or rock mass and engineering structure in or on the soil or rock mass should include all properties in the mass including all spatial variations of the properties. This would be impossible and therefore, a standard procedure is to divide a mass into homogeneous geotechnical units. A geotechnical unit is, in theory, a part of the mass in which the mechanical properties of the soil or intact rock material are uniform and the mechanical properties of the discontinuities (including anisotropy of properties) within each set of discontinuities are the same. The anisotropy of properties in a geotechnical unit should be also uniform. 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 the unit. The allowable variation of the properties within one geotechnical unit depends on: 1) the degree of variability of the properties within a mass, 2) the influence of the differences on engineering behavior, and 3) the context in which the geotechnical unit is used. In figure 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.

A ground mass containing a large variation of properties over a small distance necessarily results in geotechnical units containing larger variations in properties. This is because it is impossible or too costly to establish with sufficient accuracy all boundaries between the various areas with different properties within the mass. 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, 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 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.

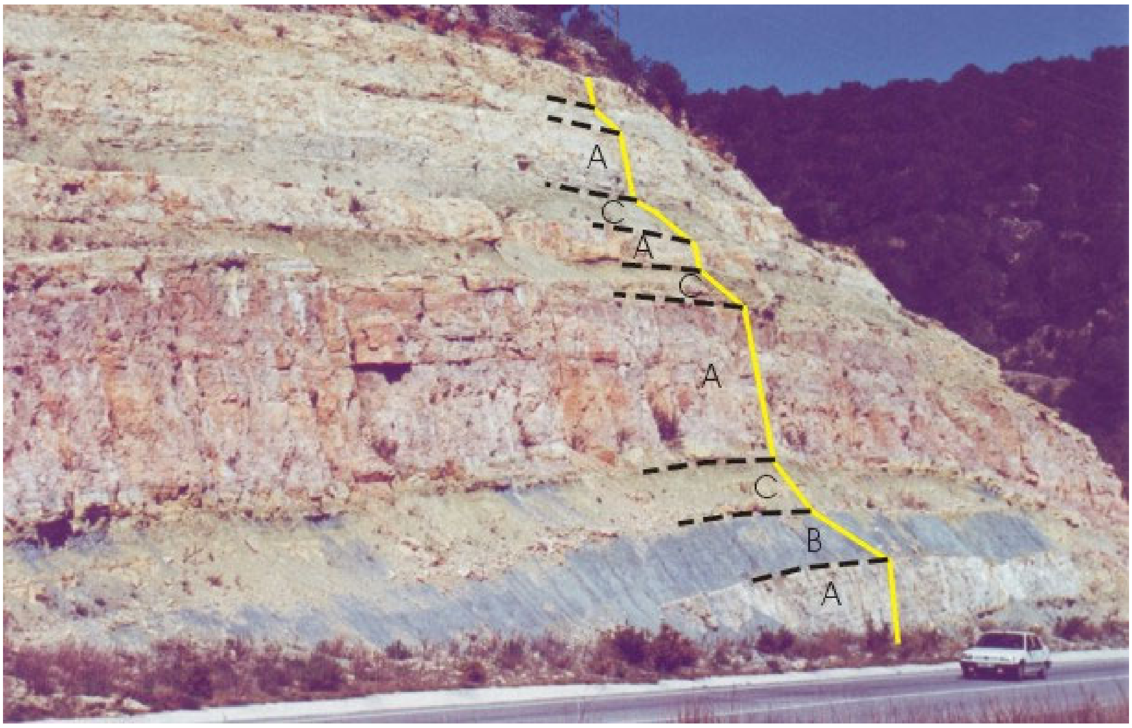

Figure 3 - Different geotechnical units present in a single slope. Bluish (B) and greenish (C) gray layers consist of calcareous shale and brownish, pinkish off-white layers (A) consist of dolomite and limestone.

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. The quality of the ‘division’ is, however, not known at present.

GEOLOGICAL UNCERTAINTY MODELING

To illustrate uncertainty in the geological modeling process that affects the subsurface project planning, two case studies with different data density are given.

North Sea Seafloor pipeline project

The data set consists of 340 shallow and deep holes that cover an area of about 15000 km^2 (134 km × 111km). Problems arise during the three-dimensional subsurface modeling of the geological units, especially with the top Holocene sand layer. The reasons are: 1) The drilling grid is irregular, but with most of the holes drilled along the design routing of the pipeline, this results in inaccuracy of the modeled geo-object when applying whatever interpolation modeling approach (ID, Kriging, TIN, etc.), 2)Only a few of the boreholes are deep. Generally, the drilling depth is down to 10 to 15 meter, this causes difficulties with a complete three-dimensional model towards larger depth, and 3) no detailed geological information is included in the borehole logs, hence an interpretation based on geological knowledge is difficult.

A part of pipeline project area is selected for testing the geological modeling process; this area covers 400 km^2 (40 km × 26 km) with 80 shallow and 2 deep boreholes. Figure 4 shows the distribution of the lithological facies in the modeling area.

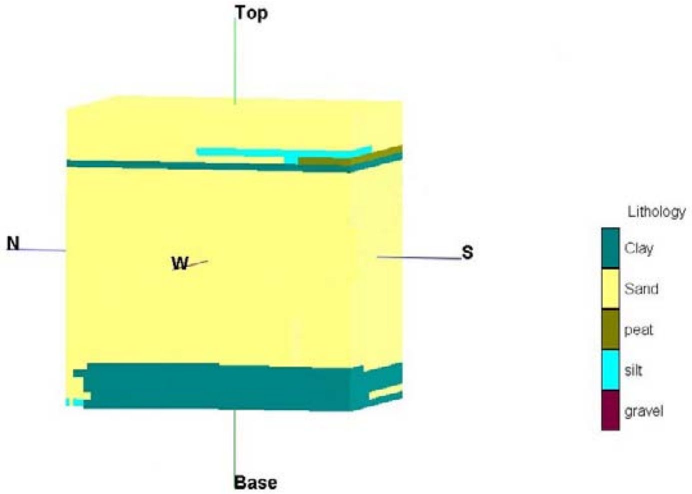

Figure 4 - Solid Lithological Model in the selected modeling area (vertical exaggeration x 500)

The Holocene layer (Dunkirk formation) is selected as study unit because of its spatial variation of materials consisting of silt, peat and sand. The different materials present will affect the routing and design of the sea floor pipeline. Based on the regional geological setting, the cross section provided with the geological map, and a detailed analysis of the log data, two simple stratigraphic models are constructed (Figure 5). In model A the top Holocene layer is further divided into two sub units, whereas in Model B only one layer is modeled. The purpose is to investigate the differences between the two models in thickness and volume of the Holocene unit.

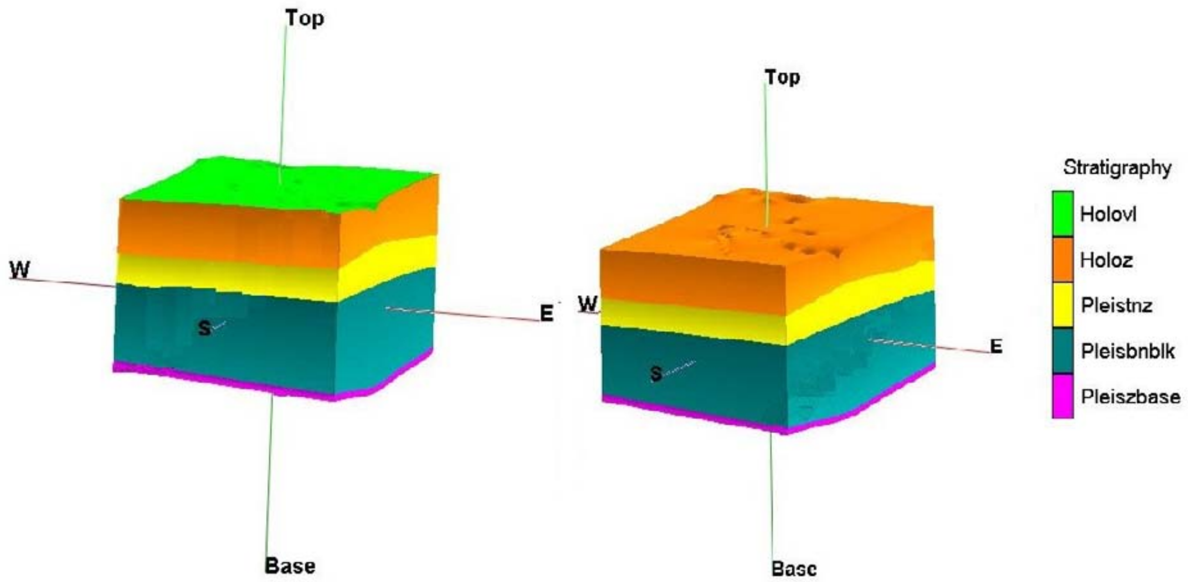

Figure 5 - Two simple stratigraphic models based on the same data. Model A (left) incorporates a sub-division of the Holocene in two units; model B (right) does not differentiate between units in the Holocene. (vertical exaggeration x 500; model grid size: 500 ×500 × 5 m^3)

Figure 5 shows a similar geometric image of the spatial distribution of the different geological units in both models A and B. The estimated thickness the Holocene unit and the estimated volume portion of the Holocene unit in relation to the total volume are roughly similar too, however, significantly different for the routing and design of the pipeline. The reasons are that the thickness of the Holocene silt and clay unit that overlays the Holocene sand unit is very thin and the thickness of this last unit varies strongly. The model grid size is, in fact, too large to model these units with sufficient accuracy in conditions of the irregular spacing of boreholes and sparse number of boreholes.

Reeuwijk Road Project

A subsurface geotechnical model is made to predict settlement of different soil units due to the changing environmental condition in combination with the loading of a new to be built road in the Reeuwijk area (The Netherlands). The available data is dense and consists of shallow boreholes with detailed logs with geological description and numerous Dutch Cone Penetration Tests (CPT). Hence, in, principle, plenty data is available for building a high quality geo-database and subsequent a reliable three-dimensional geological and geotechnical model. For this example a small area is selected of 3.2 km^2 with 63 shallow boreholes. Figure 6 shows the lithological distribution in three-dimensions.

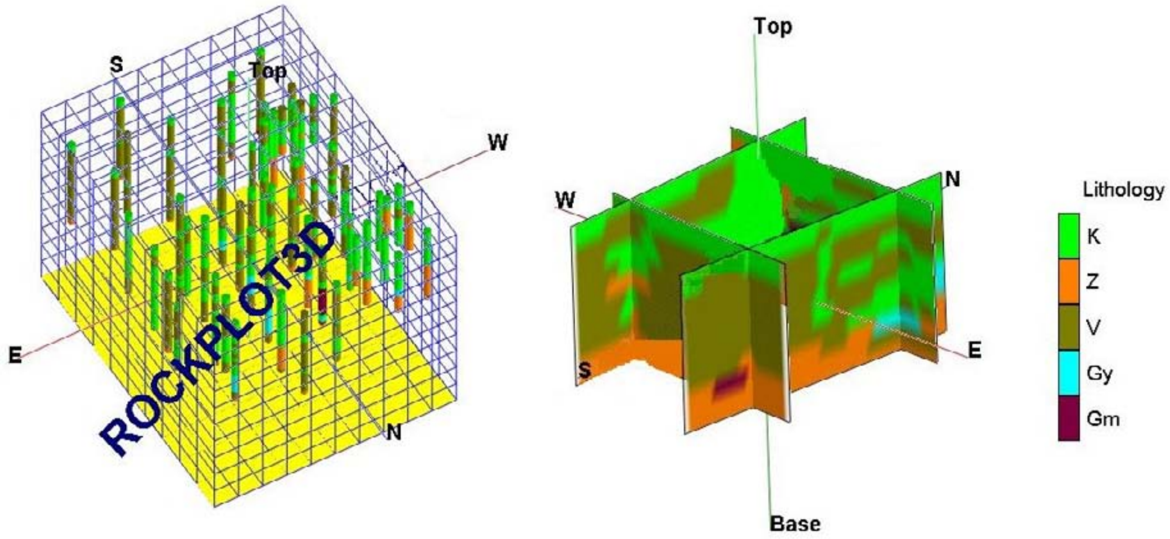

Figure 6 - Fence diagram of the solid litho-model (right) based on the known borehole data (left) (vertical exaggeration x 100).

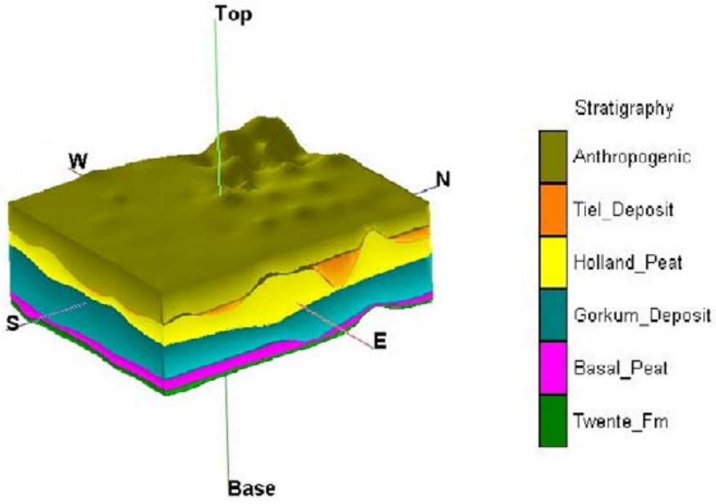

Figure 7 – Three-dimensional ground model (Reeuwijk road project) (vertical exaggeration x 100; model grid size: 50 × 50 ×1 m^3)

The subsurface geological model shown in figure 7 is based on the six geological units. Compared with the regional cross section interpreted by hand (Figure 8) some differences occur. For example, in the model of figure 6 the Holland Peat has only one horizon, but consists of various layers in the cross section of figure 8 (unit 4, black color in figure 8). Hence, although plenty of data is available the geological interpretation is fully determining the interpretations of the lithological spatial variation.

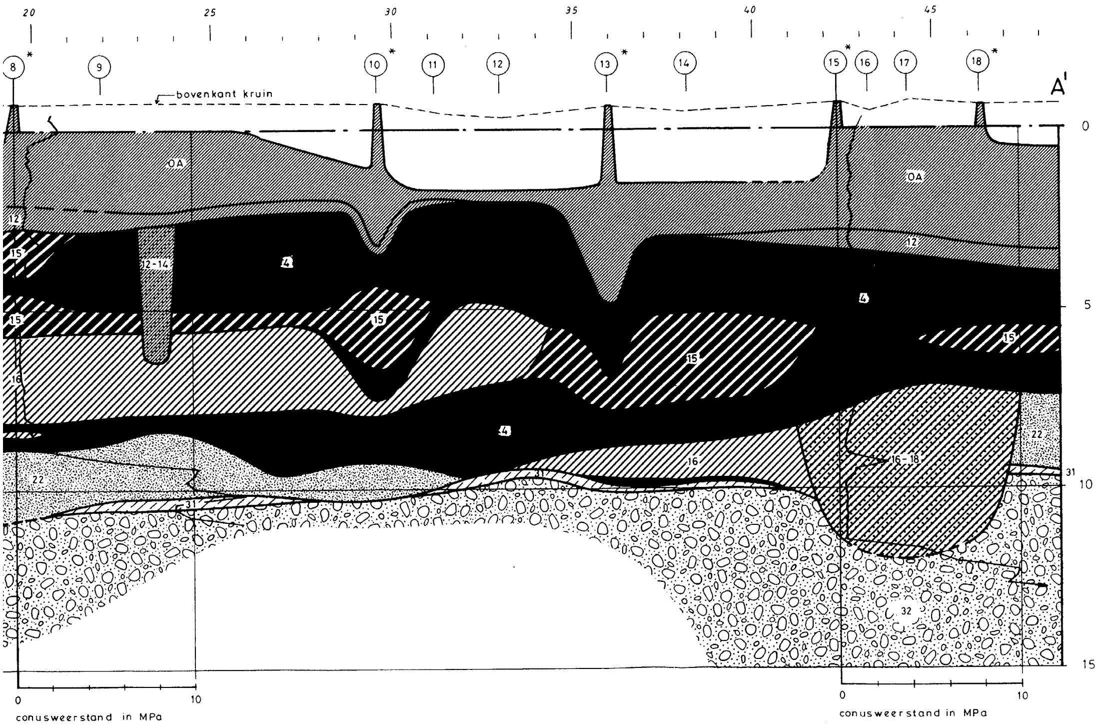

Figure 8 - Cross section Reeuwijk Road Project (after: Geological regional report of The Netherlands)

LIMIT TO SUSTAINABLE PLANNING

As shown above it has to be accepted that ground behavior cannot be established and forecasted with 100 % accuracy. Therefore, the best is that ground models are associated with an uncertainty or likelihood index. The likelihood index should be determined based on reliability factors for data, interpretation, and model interpretation parameters. At present such likelihood indexes are not satisfying, in particular, because the reliability of model interpretation parameters cannot or only partially be established. Without a proper indication of uncertainty or likelihood of subsurface models sustainable planning will be limited.

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