Visualization for improved reliability of three-dimensional geological models

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Abstract

Results of three-dimensional geological modelling of the offshore geotechnical site presented in the paper illustrate the interrelationship between geological modelling and visualization. A geological model of the site was constructed and continuously updated using an increasing amount of information with the objective of simulating on-line interpretation of geology during the site investigation campaign. Reliability of the geometrical model created was qualitatively assessed using appropriate visualization tools.

The quantitative assessment of uncertainty of the geological model was done by conditional simulation. Geological variables of interest across the site were simulated in two and three dimensions and postprocessed results compared with the previously created geological model. Applicability of different tools for visualizing uncertainty of geological models is discussed.

The results obtained showed that visualization provides an efficient way of checking the integrity of spatial geological models. However, building up consistent three-dimensional models, even in the case of a moderately complex geological setting, requires much larger input by the interpreter than traditional, two-dimensional interpretation. Furthermore, visualization, especially when combined with a quantitative measure of uncertainty, can reveal inconsistency of the geological interpretation and therefore significantly contribute to the better planning of future investigations related to civil engineering projects.

1 Introduction

Developments in the field of computer graphics have considerably influenced the way of presenting and interpreting geoscientific data. The introduction of
Visualization and Intelligent Design in Engineering

Geographic Information Systems (GIS), including their visualization capabilities, has had a major impact on the management and analysis of geoscientific data. The advantages of using GIS technology in geosciences are numerous, but their application is generally restricted to two-dimensional spatial analysis. Thus, GIS is an invaluable tool in a map making exercise, but often inappropriate for site-specific studies when information in the third dimension becomes available.

Three-dimensional character of geological features and rapidly expanding computer technology initiated development of more specific software tools for spatial interpretation in geosciences. Such packages are developed for different geoscientific disciplines and they provide approximately the same basic functionality. Essential functional components of these systems are: geological modellers, tools for property distribution modelling and visualization tools, including 3D graphics. It has been proposed to name such systems three-dimensional GeoScientific Information Systems (3D-GSIS) in order to distinguish them from GIS (e.g. Turner[10]).

3D-GSIS have been mostly employed in the mineral and oil industries. The mineral industry has already used 3D software for orebody modelling and mine planning for already a few decades (Gibbs[5]). The oil industry utilizes 3D software tools for two purposes: (1) reservoir characterization and 3D modelling (Phillips[8], Geobyte[4]), and (2) processing 3D seismic data (Brown[2]). Several examples of the geometric modelling of complex geological structures and their visualization, such as a salt dome (Renard & Gabriel[9]) or an overthrust (Aminzadeh et al[1]), have been reported.

Wide use of 3D-GSIS in the mineral and oil industry has not yet expanded to the other fields of potential application such as geotechnical site characterization. This paper makes an attempt in that direction. It presents the results of the geological modelling, both deterministic and stochastic, of an engineering site and discusses the role of enhanced visualization in estimating the model reliability.

The need for enhanced visualization is crucial in the case of a complex geological pattern, such as the tunnelling in a complex Alpine structures (Mayoraz, Mann & Parriaux[7]), but it should not be underestimated in the case of moderately complex geology either. The data upon which a geological interpretation is based are almost never enough for a unique interpretation. Therefore, the model created should pass a visual check which affirms that it is a likely one because it is consistent, it matches all hard data, it fairs soft data and it is approximately in agreement with the interpreter's expectations. Such a model stands a good chance of being reliable for further use for whatever purpose.

2 Some aspects of geological modelling

The objective of the computer modelling of geology is to create a spatial geological model which may consist of both surfaces and volumes. Geological
surfaces are used to represent features such as faults and geological boundaries, while the volumes represent three-dimensional objects such as a geological unit, an orebody or an aquifer. The distinction between geological surfaces and volumes compared to those used to model objects in mechanical engineering or architecture is in their irregularity. In most real life cases it is neither possible nor practical to model entirely the irregularity of geological features. The main reason for this are sparse input data sets used for modelling.

Input data are usually available in the following forms: (1) as a set of scattered points, (2) line-type information (e.g. borehole log), (3) surface information (direct observations by mapping, remote sensing, geophysical measurements), and (4) regularly sampled volume information, which is obtainable only by 3D seismics and performed almost exclusively in the oil industry.

Automatic routines which use sparse, fragmented and usually disseminated pieces of information to create consistent, three-dimensional geological models are currently not available. Future developments will show whether systems for automatic interpretation can prevail over the current interactive modelling systems which rely on human expertise.

3 Geological modelling for a civil engineering project

A site investigation programme performed within the scope of a civil engineering project included 20 boreholes, about 200 soil samples and laboratory testing. The total area of the site is about 2 km$^2$ and the depth of the boreholes is up to 30 m. The results of site investigations revealed the presence of a moderately complex geological setting. For the successful execution of the project it was critical to determine the spatial distribution of sand layers across the site. Preliminary interpretation of geology on cross-sections showed the existence of five sand layers, some of them non-continuous over the area of interest. The degree of geological complexity required construction of a three-dimensional geological model of site geology. The relatively small number of boreholes and the discontinuous character of sand layers would make an attempt to interpret geology using automatic 2D contouring unsuccessful. Therefore, as in the majority of real-life cases, the interpretation of geology had to rely on the expert knowledge and the experience of the interpreter.

4 Visualization of geology

Modelling started with building up the framework model, i.e. fence diagram, and then progressed towards the construction of a full three-dimensional solid model of sand layers. Lynx Geoscience Modelling System was used for geological modelling (Lynx[6]) and Wavefront’s Data Visualizer to visualize the results (Wavefront[11]).

Initial geological interpretation on cross-sections was immediately put in spatial context and visualized from different viewpoints. In that way a good
appreciation of general spatial relationships was obtained. Detected spatial patterns facilitated the choice of modelling technique used to construct the 3D model of the sand layers. An interactive approach to the modelling was adopted and the orientation of sections was determined considering the directions of geological continuity. The 3D model of the sand layers was progressively build up as a set of solid components and the intermediate results were visually checked (Figure 1). The result of geological modelling was a consistent 3D model of the sand layers (Figure 2).

5 Simulation of geology

The second part of the project included the reliability estimates of sand volumes. For that purpose a stochastic simulation technique was used. The technique aims at drawing equally probable realizations of a random variable, i.e. variable of interest, over the site in such a way that the statistics modelled from the data are approximately matched. It was important that realizations honour the sample data at their locations and therefore conditional simulation algorithms were used.

Two different approaches in conditional simulation were performed:

(1) Simulation of sand thickness, representing a continuous variable across the site, using Sequential Gaussian Simulation. This simulation was performed in 2D space.
Figure 2: The upper sand complex of the geological model is partly cut away to expose the lower sand complex.

(2) Simulation of the presence or absence of sand in volume elements, using an algorithm for Sequential Indicator Simulation of a Categorical Variable. This simulation was performed in 3D space.

The inference of the sample statistics and the spatial variability of the studied variable required as input data for the simulation is of no direct relevance to this paper and is not presented here. The algorithms utilized in the analysis are from the Geostatistical Software Library (Deutch & Journel[3]) where they are thoroughly explained.

The post-processed results of conditional simulations of importance here are: (1) a single realization of the simulated variable, (2) the average of the realizations, and (3) probability that a cutoff value is exceeded.

6 Visualization of uncertainty

The objective of the visualization is to combine the deterministic geological model and the post-processed results of conditional simulation in such manner as to check the consistency and reliability of the geological model. The results were visualized as follows:

(1) In 2D space, in the form of maps showing:
   a) Contours of sand thickness overlaid on a pixel map, showing a particular realization of the stochastic simulation.
   b) A contour of a specific sand thickness, set as a cutoff value, and the
probability contours of exceeding that cutoff value, as obtained by simulation.

(2) In 3D space using the following tools:

a) A set of cutting planes, oriented horizontally at different elevations and vertically (or at any other orientation) was used to slice through the 3D model. The deterministic geological model, as interpreted by a geologist was displayed in solid grey, and results of stochastic simulations were displayed in the form of probability contours (Figure 3).

b) A similar visual check to that described above was performed in 3D space. The deterministic geological model was displayed in the form of a wireframe surface (Figure 4). Results of simulations were used to construct the 'reliability box'. Within the box probability levels were displayed in the form of a solid, coloured in such a way to depict different probability levels. By moving the box over the geological model the areas where the geological model was exposed, i.e. where the reliability of the geological model fell below that defined by the box, were detected as areas which required additional checking and, possible, reinterpretation. The check was repeated for different probability levels (a & b).

Figure 3: Vertical section showing spatial position of sand complexes as interpreted by a geologist (in solid grey) and the probability contours, obtained by conditional simulation, showing the likelihood that the interpretation is correct. Probability levels are set to: p1 ≥ 0.8, p2 ≥ 0.6, and p3 ≥ 0.4.
Figure 4: A part of the geological model, displayed as a wireframe surface, and the reliability box, displayed as a solid. Grey shades correspond to the different probability levels as per Figure 3. Note that the geological model within the box is mostly exposed on a), indicating that the reliability of the model drops below probability level $p_2$, and hidden on b) indicating the opposite.
Visualization and Intelligent Design in Engineering

7 Conclusion

Visualization tools form an essential part of three-dimensional modelling systems used for geoscientific applications. The geotechnical case study presented here showed that the consistency of 3D geological models can be efficiently checked using enhanced visualization tools. This reduces the time spent in the interpretation and improves the accuracy of the models created. However, 3D modelling of geology, even when the modellers and visualization tools are advanced, is not a simple task. It requires considerable input of the interpreter, visual checking of the intermediate modelling efforts, and multiple refinements of the model. An additional possibility for checking the interpreted geological model is to quantify the uncertainty of geological interpretation and to visualize the interrelationship between the two.

8 References