3-D GEOMODELLING FOR SITE CHARACTERIZATION

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ABSTRACT-The paper present an overview of the basics of 3-D geological models, , model types, modelling approaches, modelling methodology, applications and the modelling limitations. The other related modelling aspects such as model validity and associated uncertainties of 3-D Modelling are elaborated. The implications of geomodelling for Site Characterization of engineering projects are discussed.

***KEYWORDS*-Modelling Approach, Modelling Software. Uncertainties in Modelling**

INTRODUCTION TO GEOLOGIC MODELS

The heterogeneous data gathered during site investigations, is not a straightforward information pool for decision makers and the other end-users, as it needs to be reinterpreted by experts for specific purposes. The homogenization of multiple, mostly analogous, data sets, and their subsequent integration into the modelling process to form a 3-D structure model, adds value to the existing database information. One of the advantages in a 3-D modelling system is the visualization of multidisciplinary information sets and their spatial relation in three dimensions, allowing new insights into the nature of the subsurface. It enables to visualize the geological subsurface in terms of the lateral distribution and thickness of each geological unit as well as the succession of the geological units. (Neber A., et al. 2006.).

As per the Commission of the International Association for Engineering Geology and the Environment (IAEG) working on the 'Use of Engineering Geological Models' (C25), the engineering geological models for geotechnical project are an essential tool for engineering quality control and provide a reliable means of identifying project-specific, critical geological issues and parameters. Models should form the basis for designing the scope, method and assessing the effectiveness of site investigations.According to C25, the term model in engineering geology is hypothesized as an approximation of reality created for solving a problem. It is an approximation of the geological conditions, at varying scales, created for the purpose of solving an engineering problem. C25 considers that engineering geological models encompass both “geological models” and “geotechnical models”; they involve understanding geological concepts as well as defined geotechnical data and engineering requirements (Parry S., Baynes, et al. 2014.).According to C25 the different fundamental methodologies used for the generation of these model types are:

a)**The conceptual approach** is based on understanding the relationships between engineering geological units, their likely geometry, and anticipated distribution. This approach, is based on concepts formulated from knowledge, experience, and are not related to real three-dimensional (3-D) space or time. A fundamental purpose of the conceptual model is to identify the credible engineering geological unknowns present, which can be targeted for investigation, to assess their potential hazard to the project.

b) **The observational engineering geological approach** is based on observations and data from project-specific ground investigationsdesigned using findings from conceptual models, and should present geological information in space or time verifying and refining the conceptual engineering geological model.

In particular, they should focus on potential engineering issues identified in the conceptual engineering geological model. Observational engineering geological models are particularly relevant at the engineering design stage. The observational engineering geological models can take a wide variety of forms: graphical borehole logs (one-dimensional), engineering geological cross sections and maps (two-dimensional) and spatial engineering geological models (three-dimensional) as either solid models (e.g. Turner, & Dearman, 1980.) or, digital models (Culshaw M.G. 2005.).

c)**The Analytical Model -**The analytical model requires considerable simplification of the observational model and, therefore, significant engineering geological judgment is required to ensure that representative ground conditions, including geotechnical parameters and boundaries, are adopted. The aim should be to focus on a model that captures the essence of the engineering design issues, but is still robust enough to illustrate the inherent engineering geological variability.

APPLICATIONS OF 3-D GEOLOGIC MODELS

One of the major application is geological understanding of the local geological structure, which was not possible using conventional methods. 3-D geological models can express, verify and modify conventional geological cognition/judgment/knowledge. It explain and portray complex geology in understandable formats (Berg R. C., et al. 2011). 3-D lithologic, stratigraphic, and textural models can be constructed which resulted in several new interpretations regarding the thickness, extent, and spatial 3-D distribution of the important geologic units of study area(Donald S. S., et al. 2010.). The area and volume of each defined geological body can be calculated and further analytical functions allow integrating and visualizing hydro-geological, engineering properties and physical or other parameters for each mapped units.

3-D geological modelling is being used for analysis of the subsurface geological characterization involving both geometrical structure and various parametric properties (Zhu Liang-feng, et al. 2013.). The digital 3-D attributed model are created by rigorous use of geological, geotechnical and geophysical data, geological knowledge and statistical methods (Berg R. C., et al. 2011). Attribution of physical parameters (density, magnetic susceptibility) to each representative lithology of the model can be used for computation of the 3-D gravity or magnetic contributions of the model (Marteleta G., et al., 2004.). Contoured or gridded surfaces of tops, bases, thicknesses and volumes of single or combined geological units (including artificial ground) (Culshaw M.G. 2005.). The 3-D Geological Modelling focuses on different types of visualization and predictive 3-D mapping but also provides all types of virtual cross-sectioning and predictive calculations of hydro-stratigraphical units and apparent validity inspections (Neber A., et al. 2006.).

The 3-D spatial geological model can be interrogated using simple tools available in the software to produce,

i. Horizontal slice maps at any depth and vertical cross-sections in any orientation (Culshaw M.G. 2005.).

ii. Synthetic logs and cross-sections at user-defined locations; Contoured surfaces; Isopachytes of single or combined units; Domain maps- Sub- and supracrop maps (Culshaw M.G. 2005.).

iii. A fully attributed Generalized Vertical Section (GVS). This forms the basis for engineering geological, hydrogeological and mineral potential classifications (Culshaw M.G. 2005.).

iv. Virtual sections can be calculated in highly variable positions and can be combined with subsurface and surface topographic information. The processing of such horizontal and vertical virtual sections gives a very precise positioning of distinct units or structures within the spatial model, especially of geotechnical and remediation applications. Thus it is also possible to analyse the subsurface, by creating geological maps, thematic maps, user defined cross-sections, horizontal slices in any elevation and synthetic drill holes (Neber A., et al. 2006.).

Advantages of detailed, coherent ground model are, better knowledge of the ground conditions, more control, better the assessment of risks for construction, safety, constrain design and the final costs (Aldiss D. T., et al. 2011.). The integration of geoscientific data within a single 3-D model, and the ability to display and query these data, are significant advances for project decision (Fallara F., Legault , et al. 2006.). The interpreted geological data pool can be used to develop management strategies for a wide range of sustainable ground-related issues. A detailed geo-scientific knowledge of the subsurface is essential for sustainable urban management and strategic planning, in terms of revitalization of contaminated sites, groundwater protection, and assessment of engineering conditions. The high-resolution 3-D models can be used for predictive application in the field of hydraulic modelling, environmental and geotechnical investigations. Digital 3-D subsurface models provide decision support tools for, planners and strategic decision makers. Visualization and analysis of the subsurface, by the expert geologist, - in order to deliver an easy-to-understand decision support system for policy and decision makers involved in sustainable regional planning (Neber A., et al. 2006.).

The models can be kept in a dynamic form; such that each newly gathered piece of geo-scientific information, e.g. new drillings, can be added to the existing structure-model basic data set and the model can be modified according to this new information (Neber A., et al. 2006.). The models benefit from continuous validation and upgrading of the underlying database, as well as the production of regional syntheses, integrating geological, geophysical, and geochemical models in a single platform. It is helpful to catalyze the development of knowledge by easily integrating data under a common format; and preserving the data in a unique archiving platform where it can easily be shared, seen, and analyzed (Fallara F., Legault , et al. 2006.). Various interpretive maps can be easily produced and updated with availability of new information and can be customized for specific needs (Berg R. C., et al. 2011).

MODELLING DATA

Data requirement for modelling is based on specific modelling objectives and application. Several different modelling methodologies have been developed depending on the type of data available. These methodologies, accounts for the variety of available data models and their integration in a 3-D geological model (Multi-Source Data Integration). To enhance the practical utility and the effectiveness of 3-D geological models, along with the stratum lithology, components, and grade information of geological bodies, the expression of attribute-oriented information and semantic information in 3-D geological modelling can be used (Wang Yongzhi, Zhao Hui, et al. 2015.).

The various exploration data can be used to characterize the project site. The well- characterize project site will facilitated the appraisal of engineering application.

i. Geological data obtain from site investigation, such as Punctual data like Well data (water wells, geoscientific and academic wells, and oil and gas wells), /Borehole data. The Borehole data consist of stratum lithology/stratigraphy data, stratigraphic contacts.

ii. Details of structural geology features such as interfaces and orientation data (dip, dip directions, strike, hinge lines, axial trace, and geologic faults). Surface traces of faults.

iii. 2D cross-sections geological map (digital geological cross sections), historical maps, and archaeological subsurface data, digital thematic maps topographical, geological, hydro-geological maps, structural geology maps, digital terrain data, DTM of appropriate resolution (Neber A., et al. 2006.).

iv. 3-D surfaces of formation bases, Isopachyte maps for formation (Aldiss D. T., et al. 2011.).

v. Line data such as rivers and creeks, and polygon data and outcrop data (Wycisk P., et al. 2009.).The 3-D geophysical data such as resistivity, seismic, gravity or magnetic, GPR (Ground Penetrating Radar) etc., obtained from geophysical investigations and the conventional geological data along with the structural cross sections and the structural maps can be integrated together to develop 3-D model of the structure.(Marteleta G., et al., 2004.).

vi. The geotechnical database for lithology characterization with **Physical** parameters such as, unit weight, porosity, water content, friction angle, cohesion, permeability coefficient, and friction ratio i.e. attribute information of can be modelled over the geological bodies. In situ and laboratory test results such as Cone Penetration Tests (CPTs), vane tests, dilatometer, & pressiometer tests, Physical & chemical property parameter, hydrochemistry (contaminants) monitoring data can also be used for property modelling.

MODELLING APPROACH

A wide range of software can be used for 3-D geological modelling. The methods and related software are based either on use of sophisticated statistical methods, or on traditional geological understanding (Berg R. C., et al. 2011). For 3-D geological modelling, choose software and methods that allow significant geological control on the distribution and character of the substratum being depicted. Constrains should be applied for the basic unit distributions and the characteristics of the modeled properties (Berg R. C., et al. 2011). Different 3-D modelling approaches are, geostatistically and constructive cross-section based interpolations (Knowledge based TIN - Triangulated Irregular Net Interpretation) (Wycisk P., et al. 2009.).

Modelling approaches based on Geostatistical algorithms

The methods for developing the property models typically involve geostatistical tools. Statistical methods of interpolation reflects additional information on spatial variation, but alone do not depict the complete spatial structure of specific depositional environments or geological knowledge, and so the value of this information is limited (Berg R. C., et al. 2011).

The single-stepped numerical modelling methodology requires a high concentration of boreholes, which are evenly distributed for each surface to be, modelled(Royse Katherine R. 2010.). The limitation of the type of numerical interpolation is the sensitivity to the distribution of the data, (Donald S. S., et al. 2010.). The uneven and spotty distribution of geological drilling information (Wycisk P., et al. 2009.),insufficient statistical borehole coverage (Wycisk P., et al. 2009.), (Royse Katherine R. 2010.). Another limitation of this method is that it is purely deterministic and data based.

Modelling approaches based on Constructive cross-section (knowledge-driven)

The geometrical modelling of the ground in Cognitive modelling methodology is based on cross-sections derived from the geological map, boreholes. The software utilizes a digital elevation model, surface geological line-work and downhole borehole data to construct cross sections by correlating boreholes and the outcrops to produce a geological fence diagram. The software takes into account all structural geology features such as dip, dip directions, strike, hinge lines, axial trace, and geologic faults to build the geometry of geological units (Williams, J., et al. 2008.).The modeler controls the detailed configuration of each modelled surface, not by modelling algorithms within the software (Aldiss D. T., et al. 2011.). The software provides the modeller with the ability to connect areas in the model, where there is either only partial data coverage or where the geometry of the geological units is poorly understood (Royse Katherine R. 2010.). The method can reproduce surfaces (faults and stratigraphic horizons) that not only honoured the data but also were also geologically reasonable even in areas where the data was sparse or uncertain (Royse Katherine R. 2010.).

The advantages of geostatistically based modelling are high if the coverage of borehole data is sufficient. The insufficient density of borehole data is a function of the complexity of the subsurface. Therefore, the application of 3-D subsurface models, on local or regional scale, has to be completed by knowledge-based control, as much as possible(Wycisk P., et al. 2009.).

The subsurface data available is normally very limited. Some basic geological, limited number of boreholes or probing data, rarely supplemented by geophysical data, is generally 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 availability of expert knowledge. However the correctness of the model whether on paper or in a program cannot be assessed, because of the limited amount of data available and the heavy influence of expert knowledge/judgement on the final model. The statistical analysis of the relative uncertainty with GSI3D cannot be done inside the software package. Due to the plausibility-checked cross-section network, as well as additional information from 2D mapping and expert-driven interactive remodelling, the statistically based uncertainty of information is therefore difficult to estimate(Wycisk P., et al. 2009.).

Combine Approach

The modelling methodology combining cognitive and numerical modelling can be developed to avail the advantages of both systems and to overcome the problem of having an uneven distribution of borehole/subsurface data.(Royse Katherine R. 2010.).Geostatistical Interpolation is applied within constrain defined by the geological boundaries identified with cognitive geological understanding.

There are combine Modified Approaches based on continuous ongoing research & development in the field of comprehensive 3-D modelling. The available software functionalities are not sufficient to cater the diverse requirement of modelling. The required functionalities may not be available with single software, making it essential to use more than one software in combination. The various modelling data type, modelling objectives, engineering applications are also the important factor which influence software selection and even the methodological approach to the 3-D modelling. The specific requirement may need the alternate approach to deal with, the limitations of the existing methodology or software.

VALIDATION OF MODEL

An initial test of the strength of the subsurface 3-D lithologic model is to compare the mapped surface geology to that predicted at land surface by the 3-D model (Donald S. S., et al. 2010.). The model simulated results should also be compared to the ‘‘real-world scenario’’ of the 3-D spatial model of the investigated site (Wycisk P., et al. 2009.). E.g., the evidence for validation of the modelling methodology for 3D modelling carried for the structure of the Chalk in the London Basin has come from chalk-cored boreholes from the Thames Waters Lee Tunnel and Thames Waters Ring Main extension, where site investigations suggest the presence of a major north south offset which has again been predicted by the model. In addition, a new hydrogeological model for London has found that in using the new fault model the resulting groundwater level pattern fits better (Royse Katherine R. 2010.).

An interactive comparison between modelled and measured potential fields provides a best-fit adjustment of the model geometry compatible with the different input data sets (Marteleta G., et al., 2004.). When discrepancies between computed and observed gravity fields are identified, the geology is locally reinterpreted.

UNCERTAINTY OF 3-D INTEGRATED GEOLOGICAL MODELS

The limitation of 3D Modelling is its inability to depict accurately the natural variability of geological systems or to represent uncertainty. The Conceptual Engineering Geological Model potentially involve a relatively high degree of uncertainty which is directly related to the type and amount of existing data and the knowledge and experience of persons involved. The uncertainty is rather abstract which relates to whether or not the set of concepts identified are relevant. Culshaw M.G. 2005, has define the areas of uncertainty and the broad methods for estimating uncertainty.

i. Uncertainty associated with the data (natural variability) and measurements (sampling and measurement error)
ii. The uncertainties of the modelling process (the assumptions and simplifications made).

There are three broad methods for estimating uncertainty

i. **Analytical approach**, which uses statistical theory to propagate combined uncertainties through the mathematical functions that use the measured inputs to produce the modelled outputs.
ii. **Computationally intensive approach**, where the model is calculated a number of times with a small change to the input parameters (representative of the natural uncertainty of that parameter). The result of each run of the model is stored and, with the use of suitable strategies for the choice of input parameter changes, the distribution of results for the repetitions will be representative of the uncertainty in the model.
iii. **Measurement of uncertainty on subjective and semi-quantitative data**. Geological interpretation is an example of subjective information

A simple method can be used to visualize the uncertainty associated with a modelled geological surface that accounts for both qualitative and quantitative terms. Additional drilling at the site will test the hypothesis and allow model validation. Once validated, the uncertainty estimation method can be tested on larger, geological diverse and complex environments. Another way for identifying areas of greater uncertainties is by calculating probability field. An evaluation method of geological uncertainties related to 3-D subsurface models is proposed by Tacher L., et al., 2006, for the most probable prediction (the most probable realization/ Best Guess) and tested.

ENGINEERING IMPLICATIONS OF GEOMODELLING

Proper site selection is, of greatest important in the construction of dam. The safety, stability and effectiveness of a dam, depend largely on the geological conditions at the site.

Following are the applications of 3D Geomodelling

1. The main sectors where 3-D geological models finds its application include Water, Wastewater, Waste Disposal, Contamination and Management, Hydrocarbon, and Carbon Capture and Storage, Land-Use Planning and Local Decision Making, Civil Engineering and Infrastructure, Archaeology, Mineral Resources (exploration), Research and Education and Outreach (Berg R. C., et al. 2011).
2. Integrated investigation strategies of contaminated sites (Neber A., et al. 2006.). Identification, assessment, and remediation of large-scale groundwater contamination require a detailed knowledge of the heterogeneous geological structure to predict the fate and pathways of contaminants and their potential interaction with, e.g., surface water (Wycisk P., et al. 2009.). The 3-D geomodel provide this functionality.
3. Management of groundwater resources, monitoring of water quality and all related environmental issues (Neber A., et al. 2006.). 3-D modelling allows prediction of groundwater flow and transport for an integrated environmental risk assessment (Wycisk P., et al. 2009.).
4. The development of regional hydrogeological frameworks to serve as the basis for understanding groundwater, geological hazards, and natural resources (Jacobsen Linda J., et al., 2011.).

The geological understanding developed through specifically built 3-D model can be utilized for various engineering applications.

1. The 3-D model can be used to quickly generate synthetic lines of section or synthetic borehole logs, to predict ground conditions at a particular point or on an alternative route alignment. It has also identified gaps in the dataset, assisting in the planning of continuing ground investigation (Aldiss D. T., et al. 2011.).
2. The ground characterization for tunneling in soft soils: The engineering requirements was to determine the volumes of each soil type to be encountered and its geotechnical properties, water pressures and surface settlements determination. The requirement were satisfied with the 3-D modelling functions with extensive use of external

associated routines. 3-D geotechnical models can be used for numerical calculations to verify the engineering feasibility with regard to overall stability of tunnel sections, landslide prone slope etc. (Ozmutlu enol, et al. 2003.).

3. Analysis of geomechanical TBM performance modelling and quantitative volumetric analysis of geologic units(Elkadi A.S., 2002.).
4. The selection of cost effective and safe foundation type was determined by the regional estimation of soil settlement, aided by geometrical modelling, visualization and geostatistical analysis (Ozmutlu enol, et al. 2003.).
5. The subsurface conditions and the ground- structure interaction information was acquired for foundation decision-making. The geological information (depth, extent, thickness of layers), geotechnical information (soil/rock engineering properties, unit weight, cone resistance), and information regarding the behaviour of the ground when subject to a change in equilibrium was modelled for foundation decision. The 3-D geological and geotechnical models provide the ground parameters to the soil mechanics models (Ozmutlu enol, et al. 2003.).
6. Preparation of Maps for tunnels or pipelines along the proposed design route (Culshaw M.G. 2005.).
7. Seismic risk Evaluation ,Engineering projects, Assessment of CO_2 storage capacity Assessment of geothermal potential (BRGM French geological survey)

LIMITATIONS OF MODELLING

Euro Conference in Spa, Belgium in (Rosenbaum & Turner 2003.), identified important impediments, at that time, to greater use of 3-D geological models:

- a lack of 3-D/4D mathematical, cognitive and statistical spatial tools;
- a lack of cheap modelling tools designed for the shallow subsurface that can be operated without specialist personnel
- the inability of models to depict natural variability of geological systems;

Very localized geological phenomena such as small scour hollows, relict pingo and allied periglacial structures and small channel infill cannot be easily shown at the intended resolution of the model unless a borehole proving the structure is included in a cross-section (Mathers S.J., et al., 2014.).

CONCLUSION

Three-dimensional integrated geological modelling cannot be defined, and followed, like a cookbook recipe. Each project or study area requires a different approach based on the objectives and the available databases. The specific engineering application and the multiple data with diverse quality and quantity may force to adopt combine use and integration of various software. This requirement shall also lead to the adopting new methodologies, and approaches to the 3-D geological modelling.

In spite of the limitations with 3-D modelling can prove to be the valuable tool for better geological characterization and related project decisions. Convergence of different modelling software capabilities, better data integration along with use of advance geostatistical techniques blended with cognitive knowledge are required to overcome these limitation.

FUTURE SCOPE

The ongoing research and development in the field of modelling is working on the following aspects.

1. An integrated system of tools and techniques from 3-D GIS, improved visualization and artificial intelligence components, will bring the necessary power and functionality to support effective decision making in large ground engineering projects (Ozmutlu enol, et al. 2003.).
2. Finite Element modelling (FEM) enables surface or volumetric representation using nodes generated from control data (boundary conditions). The ease of exchange of model structures between 3-D GIS and FEM applications is limited to simple situations, but can facilitate the effective use of subsurface information in the design and construction stages (Ozmutlu enol, et al. 2003.).

These feature will definitely improve the characterization capabilities of the geomodel.

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