

## An Overview of 3-D Geological Modelling, Part III Software Applications in 3-D Geological Modelling

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**Abstract:** Various software available for 3-D geological modelling, corresponding methodological workflows, their combinations, the related generic modelling issues such as different modelling approaches (based on data availability and the modelling objectives), are discussed. The commonly used software and the methodologies as adopted by various geological organizations and researchers are tried to couple in the different groups. The methodologies are streamline into simplified workflow procedure with case studies. The case studies are selected considering their relevance, usefulness showing the gradual developments in the field of 3-D modelling. The requirements and the uniqueness of these modelling procedures are mention wherever appropriate.

**Keywords:** Geostatistical modelling, GSI3D, modelling Software, Software Combinations.

### I. Introduction

The ideal software environments for 3-D geological modelling should have following prominent functionalities,

- Multi-source data integration to synthesis geological databases with organization and data management,
- Constructive knowledge-driven modelling capabilities,
- Geostatistical Interpolation and simulation of geological characteristics.
- Interactive volumetric construction with constrain modelling i.e. mapping honoring geological rules.

The most common software packages used for building 3-D geologic maps and models in many geological survey organizations (GSOs) include, ArcGIS, GoCad, EarthVision, 3-D GeoModeller, GSI3D, Multilayer-GDM, and Isatis. Many other software packages are also used in GSOs worldwide as part of modelling workflows and these include software for GIS, Geostatistical Analysis, Visualization, and Property modelling[9]. Software and the methodologies as adopted by various geological organizations and researchers can be group into following categories,

Table 1. Grouping of Software and the modelling methodologies

<b>2</b>		<b>3-D modelling Approaches</b>
<b>3</b>		<b>Geostatistical modelling Techniques</b>
	3.1	Geostatistical method with simple database application (MS Access).
	3.2	Statistical Interpolation Technique with Isatis software.
	3.3	MOSYS modelling System.
	3.4	Modelling with 3-D GIS (Geographical Information System).
	3.5	3-D GIS based 3-D Geological Models for Attribute-oriented Information
	3.6	Modelling with 3-D GeoModeller.
	3.7	Modelling with GoCad (Geological Object Computer Aided Design).
<b>4</b>		<b>Combination with other software</b>
	4.1	GSI3D (Geological Surveying and Investigation in 3-D) withGoCad.
	4.2	3-Dmodelling through data integration between GIS and GoCad.
	4.3	3-D GIS with Lynx Geoscience modelling System.
	4.4	3-D-GSIS (Geoscientific Information Systems) applications in Lynx-GMS.
	4.5	Model Vision, GoCad, Geomodeller and other software combination.
	4.6	Multiple Software Packages for Addressing Geological Complexities.

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 selected case studies from the various fields of modelling application highlights the same. The work presented here is mainly about the modelling workflows adopted in the different modelling methodologies. The discussion is defining the concise modelling procedure and how it has been adopted considering the geological concepts.

## **II. Various 3-D modelling Approaches**

GSI3D methodology forms the essence of geological knowledge based 3-D modelling whereas Geostatistical Interpolation method provide mathematical algorithm based statistical and spatial data analysis to achieve the property (parameter) distribution for each geological unit ensuring data integrity. The discussion on the applications of software will be incomplete without mentioning the Alternate 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 specific case study may need the alternate approach to deal with, customised requirement or the limitations of the existing methodology or software. The Alternate Modified Approaches to address the modelling software issues are adding the new dimension to the 3-D modelling. The detail elaborate discussions on the modelling approach and the same authors in paper named, "An Overview of 3-D Geological modelling Part II, present methodology for GSI3D, Geostatistical Interpolation method and the Alternate Modified Approaches. *Summary of Major 3-D Geological modelling Methodologies*". The readers are advised to refer the same, to have understanding of these modelling approaches.

## **III. Geostatistical modelling Techniques**

Various geostatistical modelling software are available. The suitability and the selection of particular software however depends upon the type of the data and the modelling requirements. The various case studies are discuss, to explain the generalised software workflow and their applications.

### **3.1 Geostatistical method with simple database application (MS ACCESS)**

Case study of 3-D geological modelling at urban scale is discussed for mapping of ground movement susceptibility from gypsum dissolution – The example Paris (France)[17]. The methodology uses geostatistical interpolation method and MS Access as data base application. The methodology and procedure involved following generalised steps.

Construction of a 3-D geological model by the geostatistical method is through interpolating the bottom and top surfaces of the modelled geological formations from borehole data and compiled geological maps. The geological maps were used for digitizing the boundaries of reference lithostratigraphic units. The boundaries were locally be modified according to the boreholes and other available geological data. These boundaries allow to constrain the interpolated surfaces, and to limit the interpolations to the zones of different units. In general, the formations are logically superimposed following the stratigraphic order. However, in the case of sedimentation gaps or erosion, modelled surfaces are likely to "cross-cut" one another. The logic of combination leads to cut the sedimentation surface with the erosion surface considering the geological understanding.

### **3.2 Statistical Interpolation Technique using Isatis software,**

Geological Survey of the Netherlands defines two modelling methodologies, namely Digital Geological modelling (DGM) and GeoTOP (3-D Volume Model of the Upper 30 Meters) [16]. The methodologies are based on use of statistical Interpolation technique.

#### **3.2.1 Workflow for Digital Geological modelling (DGM)**

Stratigraphic Interpretation is performed by assigning the lithostratigraphic classification to the individual sample intervals. Which is subsequently used for interpolation and modelling. Fault mapping for every lithostratigraphic unit, that have influenced the base of the unit are selected and used as "barriers" in the interpolation process. The depths of the depositional base of each lithostratigraphic unit, as derived from the borehole data, are interpolated to raster surfaces using the "block-kriging" algorithm. The top surface follows indirectly from the joined basal surfaces of overlying units when all units are stacked. Block kriging alone may fails to produce a result that corresponds to the geological concept. Therefore, additional information is taken into account, including maps with the maximum spatial extent of each lithostratigraphic unit; trend surfaces showing geological structures (basins) or trends (dip direction and dip angle); and guiding points ("synthetic

boreholes”) inserted at locations with specific geological features (e.g., units that pinch out or incised channels). In the final step, the basal surfaces of each unit are stacked in a stratigraphically consistent way. The preferred choice of the type of intersection to apply depends on the geological concept that must be appropriately represented. The stacking process is performed within Isatis software, using grid-to-grid operations that are also available in standard GIS software.

### **3.2.2 Workflow for GeoTOP (3-D Volume Model of the Upper 30 Meters)**

For stratigraphical interpolation of boreholes, Python scripts were developed that use lithologic borehole descriptions within a context of digitized geological maps to assign lithostratigraphic labels to the borehole intervals. 2-D bounding surfaces are constructed by, a stochastic interpolation technique is used (sequential Gaussian simulation), which allows uncertainty to be estimated. The 3-D interpolation is conducted for each lithostratigraphic unit separately using a stochastic interpolation technique called sequential indicator simulation. In addition to the modelling the measured values of physical and chemical properties such as hydraulic conductivity, the reactivity of sediments (contaminant plumes) can be assigned to lithostratigraphic and lithofacies units, to obtain insights into the spatial variability of these parameters in three dimensions.

### **3.3 Applications of MOSYS modelling System**

The proposed modelling approach to the 3-D geological modelling of sedimentary basins was integrated within the MOSYS modelling system as algorithmized workflow [14]. Script based MOSYS system for the generation of a three dimensional geological structure was used. The script commands execute specific higher-level geometrical, geological or computational tasks and allow for the achievement of repeatable modelling results easily, with minimum programming experience.

Model geometry was constructed layer-wise on a 2D unstructured triangular mesh where each layer is represented as a volumetric element. The triangular mesh incorporates characteristic features such as fault lines and borehole points as mesh nodes. Known faults were scripted as dissecting lines where the 2D mesh was cut along them, duplicating the mesh nodes along the lines. Borehole locations in the mesh structure were incorporated as single points. Data interpolation was done by linear interpolation. Extrapolation was handled by extrapolating the average value trend within the data set to the area where values were not defined. The layer topography and fault displacements of each layer are transferred within each tectonic sequence following the stratigraphy and structural concepts of the geological column. The topological relations of all model layers are controlled by relationships between sedimentary layers and erosion interfaces.

### **3.4 Applications of 3-D GIS (Geographical Information System)**

The objectives of an Integrated 3-D GIS Model of the Yellowknife Camp study was to check the advantages of a three-dimensional Geographic Information System model (combining 3-D subsurface data with surface information) to provide a framework for concurrent structural and alteration studies [11].

The 3-D GIS model developed for the project incorporates surface features, surface geology, structural geology, point sample data (assay and whole rock geochemistry), and exploration drilling. 3-D GIS can be used to display surface topography as defined by contour data or gridded elevation data points. The geological base map was digitized and updated where more recent mapping or detailed examination had revised the interpretations. Surface geological maps are draped and extruded to the topography. Thus showing the relief of various structures resulting in three-dimensional features. Three-dimensional models of the major structural units (especially faults, shears, and dikes) have been developed from the existing surface geology maps, downhole picks from drill hole data, and plans. A complete record of the surface and underground exploration drilling at site has been included in the 3-D GIS model. This dataset has highlighted potential gaps in exploration; the focus was on longer more carefully logged and evaluated exploration holes. The checked data were included for all available drill holes and are represented using a color code on the three-dimensional representations of the drillhole traces. At the site, an extensive detailed model has been created of the dikes in an effort to understand the stratum complexities.

### **3.5 3-D Geological Models for Attribute-oriented Information Expression [18].**

The method for 3-D stratum modelling using stratified stratum information and lithologic information of geological bodies was proposed. Smoothing methods for the stratum 3-D model based on the modified butterfly subdivision surface modelling technique was established. 3-D voxel models for geological bodies were established based on the tetrahedron mesh discretization technique in the extended advancing-front method. A method for obtaining a 3-D voxel model of geological bodies was proposed, as well as a method for generating an irregular data field to describe orebody components and grade information. Combined with the direct volume

rendering technique, which allowed the visualization and analysis of orebody components and grade information.

The geometrical morphology of geological bodies tends to be complex and uncertain, so topological errors will be generated after the treatment of 3-D stratum models. Based on the Half-Edge data structure, an effective topology checking and repair method for 3-D stratum models was proposed. In order to address the needs for expressing and analyzing geological attribute information, considering the complexity of objects in geoscience, the mesh advancing-front method is employed. By embedding geo-science analysis and calculation models in 3-D voxel models, the corresponding geo-science characteristics known as the attributes of mesh nodes can then be calculated. Finally, a regular or irregular data field is structured. Based on the Marching Cube, visualization method for irregular data fields, a direct volume rendering method for irregular data field that can exclude occluded units is proposed, which is calculated based on geo-science models.

### 3.6 Geological Editor, (BRGM French geological survey)

#### 3-D geometrical modelling using 3-D GeoModeller software [6], [12].

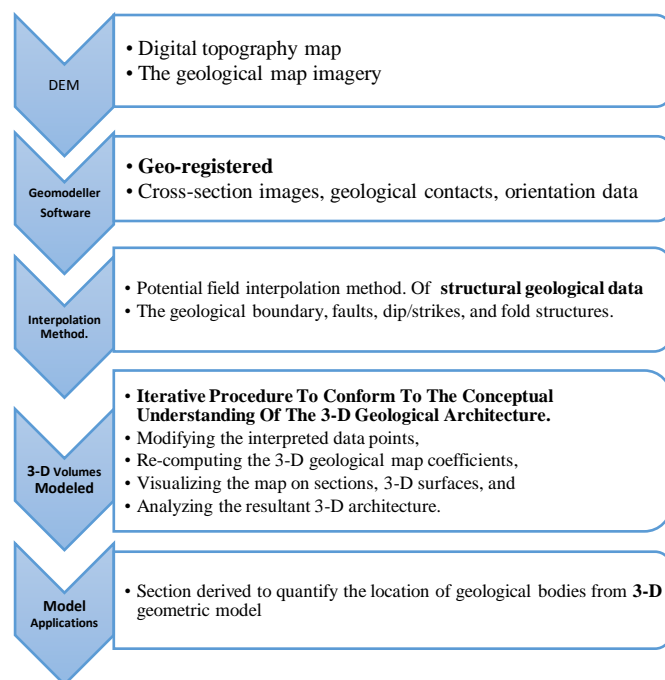


Fig.1 Methodology based on GeoModeller software(modified after [6].)

3-D GeoModeller (Bureau de Recherché Géologiques et Minières French geological survey) - Using a mixed data-driven and expert-controlled 3-D modelling approach, 3-D GeoModeller allowed simultaneous data integration, synthesis, and geological interpretation of geophysical data in conjunction with 3-D geological mapping. [7].

1. The case study of integrated 3-D geophysical and geological modelling of the Hercynian Suture (south Brittany, France) combines geological knowledge (surface geology) and geophysical imagery (gravity data, and a deep seismic reflection profile) at the crustal scale to model the 3-D geometry [12]. The proposed 3-D model has an internal geometrical consistency, compatible with available geophysical data (seismic and gravity), and integrates the geological knowledge at a regional scale.
2. The 3-D geometrical model is built in a geo-referenced system; with 3-D integration of (i) a DEM, (ii) a simplified geological map (lithological contact information), (iii) accounting foliation dips measured within the different units (local gradient information), and (iv) gravity cross-sections (geophysical parameters if any). Lithological units are described by a pseudostratigraphic pile, intended to image the geology and structural relationships. Based on the geological knowledge, other profiles have been modelled.
3. To compute the 3-D gravity or magnetic contributions of the model, physical parameters (density, magnetic susceptibility) can be attributed to each representative lithology. The interpretation of the seismic profile has been used to constrain the geometry of the structures at depth. The geometry of the lithological boundaries was adjusted performing 2D gravity modelling along the geological sections.

4. In the next step, integration in the 3-D geometrical modeller produces consistency between all cross-sections and the geological map. Based on a specific geostatistical interpolation procedure, the Geological Editor interpolates the local input data to the whole 3-D space to build a regional-scale 3-D geometrical model. In the model, lithological units are volumes to which physical properties (density, susceptibility) are attributed.
5. Finally, using the densities reported, the 3-D gravity contribution of the resulting 3-D model is computed and compared with the Bouguer anomaly. When discrepancies between computed and observed gravity fields are identified, the geology is locally reinterpreted, the model being interactively adjusted in 3-D. The 3-D gravity or magnetic contribution of the model can thus be calculated and compared to the measured potential fields for further interactive adjustment of the model geometry, to improve the accuracy of the geological model.

### **3.6.1 Application of 3-D GeoModeller**

The case study of Geological modelling from field data and geological knowledge coupling 3-D potential-field interpolation and geological rules is discussed [2]. The 3-D GeoModeller software is used for the modelling. The methodology consists of following generalised procedure. The method has been developed to model geology using the location of the geological interfaces and orientation data from structural field. Data are interpolated through a potential field continuously defined in the entire 3-D domain. The 3-D geological space is described through a continuous potential field scalar function where geological boundaries are reference isopotential surfaces and structural dips define gradients of the scalar function. Both types of data are cokriged to interpolate a continuous 3-D potential-field scalar function describing the geometry of the geology. Thus, the spatial continuity of the potential field is ensured by implementation of the cokriging using a unique neighbourhood approach. Geological interfaces are particular isosurfaces extracted from the potential field. They may have any kind of 3-D geometry: multilayer type, recumbent folds, complex intrusions, etc. Geology contact locations set the position of reference isovalues while orientation data are the gradients of the scalar function. Geometry of geological bodies is achieved by discretizing reference isovalues. Faults are modelled using the same method by inserting discontinuities in the potential field. Potential fields can be combined to model realistic, complex geometry: scalar functions representing separate geological series are merged automatically using geological rules to enable fast computation and easy update of interpretation. Geological rules are defined to model complex geology where formations overlap onto or erode another. These rules are also used to automatically assign the right geological interface between two consecutive formations.

### **3.7 GoCad (Geological Object Computer Aided Design) as GeoModeller**

The software packages utilized in the modelling workflow include mainly GoCad (Paradigm) for modelling, along with the allied applications of ArcGIS (ESRI), MapInfo (Pitney Bowes), Access (Microsoft) for data processing. Methodology is presented as Multi-scaled 3-D Geological modelling with a Single Software Solution and Low Costs solution [3]. The Manitoba Geological Survey (MGS) proposed following methods for 3-D Geological modelling

1. Cross Section Method.
2. Direct Data modelling Method. In addition,
3. Digitization modelling Method.

#### **1. Cross Section Method.**

- i. The data are formatted and plotted onto cross section traces. Each cross section trace is manually interpreted to define unit tops, which filters the data of variable quality based on local trends.
- ii. The interpretation is captured along the cross section trace and recorded as “virtual drill holes” or predicted stratigraphic points (PSP), which provides a grid of PSPs for the project area. These data are then imported into Microsoft Access and formatted. The formatted PSPs are imported into **GoCad** modelling software, which combined with unit edges to create a model surface.
- iii. Model surfaces are then used to “erode” GoCad stratigraphic grids (S-grid) to create a filed volume or “solid” for each modeled unit.

#### **2. Direct Data modelling Method**

The stratigraphically significant deep, detailed drill holes are selected, and formation tops are re-picked for consistency over the study area. The resulting data set of formation tops and a data set of formation edges form the basis of the model. These stratigraphically filtered data are imported into GoCad for modelling.

#### **3. Digitization modelling Method**

To convert the existing paper 3-D model in the atlas of the Western Canada Sedimentary Basin (WCSB) model into a digital 3-D model, structural contours and formation edges for each of the geological periods were scanned from the WCSB and digitized. The digitized contours were tagged for elevation and, along with the edges, were exported into GoCad and are modelled. In each of these methodologies, the size of

the data cells and/or triangles in the TIN of the resultant model are dependent on data quality and distribution, model size, and available computing power.

### 3.7.13-D geological modelling from boreholes, cross-sections and geological maps.

The case study, discuss a methodology to integrate different types of accessible geological information (boreholes, outcrops, cross-sections, geological maps) in a 3-D geological model is presented[8]. The developed methodology has been implemented within a system based on ArcGIS as geographic information system, GoCad as a Geomodeller and a simple database. Data pre-processing including data collection, structuring and reinterpretation. Tailor-made tools to manipulate control and validate borehole data through visual comparison of logs of neighbouring data. Creation of consistent digitized spatially reference dataset in a consistent geological interpretation framework. A DEM used to model the topographic surface and assign new elevations to all data within a GIS environment.

#### Methodology consist of following steps

1. Maps and cross-sections are digitized and boundaries created using 2D topology rules to ensure the

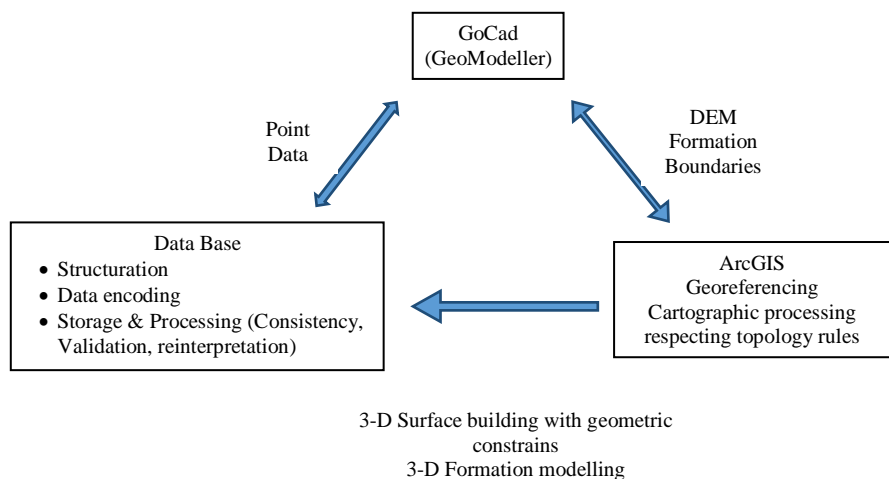


Fig 2. System Architecture, for GoCad, ArcGIS & Database

- geometric consistency.
2. Data are imported in the Geomodeller to build surface or volumes with complex geometry of geological folded and faulted structures).
3. The geological extents and cross-sections are used to model the geological surfaces (fault, top or bottom layer, etc.) The punctual data are used to constrain the surface shapes within their extents.
4. From the boundaries, formation extents are built using borehole descriptions to estimate the layer thickness in areas where it does not outcrop. Then, these formation extents are used in GoCad to model the limits of formation tops or floors
5. The surfaces are modelled using the Discrete Smooth Interpolation (DSI) algorithm to compute the location of nodes
6. During the process, geometric constraints are applied manually on these surfaces to control the movement during the interpolation. DSI equations minimize roughness criteria while taking into account the constraints.
7. From these surfaces, every solid geological body is created using stratigraphic grids, giving birth to a 3-D geological model of the area.

## IV. Combination with other software

Functional capabilities of different software and even combine knowledge & geostatistical interpolation based approaches can be combined together to harness their respective advantages.

### 4.1 Combination of GSI3D (Geological Surveying and Investigation in 3-D) with GoCad

The single-stepped numerical modelling methodology requires a high concentration of boreholes, which are evenly distributed for each surface to be modelled. However, the required density of data may not be available. In addition, the numerical modelling techniques may not respect geological understanding in such a situations. The modelling methodology combining cognitive and numerical modelling was developed in order to

overcome the problem of having an uneven distribution inadequacy of borehole and other subsurface data. The applicability of GSI3D can be further extended with additional geological structural data such as faults by combining it with other software such as GOCAD to use Numerical-modelling methods [15].

1. It was found that by using the GSI3D cognitive approach with its methodology based on the long-standing relationship between the geological map and cross-section generation, a structural model could be achieved. The methodology can be combined together the functionality of both GSI3D and GoCad. This approach allowed the modeler to capture an interpretation of the geometry and thickness of each geological unit [10], to pick out areas of faulting and generalised the faults into a coherent fault pattern, using numerical techniques in GoCad, to smooth and cut the model by the generated fault pattern. The method can reproduced 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.
2. Fault traces and the resulting fault network the data can be exported into GoCad. It operates on the premise that the geometry of any geological object can be defined by a set of points. An object is modelled by the links connecting these points. GoCad programme based on the Discrete Smooth Interpolation algorithm (DSI) is designed to model the geometry of complex geological objects and account for any constraints, such as boreholes data, placed upon it. The data imported consist of digital cross-sections generated in GSI3D, the original borehole data, which were all imported into GoCad as 3-D geo-registered point data. The NEXTMAP (Britain digital terrain model dataset) DTM (Digital Terrain Model) was brought in as a surface and the generalised fault network work and digital geological line work was imported in as 3-D line datasets. Data exchange between the two programs (GSI3D and GoCad) was simply made through existing file exchanges. This data provided the constraints to the final modelled surface produced in GoCad.
3. Using scripts 'wizards' within GoCad, triangulated surfaces were generated for each geological formation and fault plane. The surfaces were constructed using the DSI algorithm to compute the location of the nodes. This algorithm produces a geometry, which is smooth, but can also take account of a set of constraints, such as the borehole and cross-section data. Once this is done, a series of steps are followed which removes cross-over errors between the surfaces. This is done through either applying thickness constraints or moving surfaces above or below a reference surface i.e. the surface with the highest quantity of good-quality well-distributed data [15].

#### 4.2 3-D modelling through data integration between GIS and GoCad

A case study of 3-D reconstruction of complex geological bodies [19], is discussed to study integration between GIS and GoCad. Cartographic geological and structural data collected in the field and managed by Geographic Information Systems (GIS) technology can be used for 3-D reconstruction of complex geological bodies. Using a link between GIS tools and GoCad, stratigraphic and tectonic surfaces can be reconstructed taking into account any geometrical constraint derived from field observations. Complex surfaces can be reconstructed using large data sets analysed by suitable geometrical techniques. Three main typologies of geometric features and related attributes are exported from a GIS-geodatabase: (i) topographic data as points from a digital elevation model; (ii) Stratigraphic and tectonic boundaries, and linear features as 2D polylines; and (iii) Structural data as points.

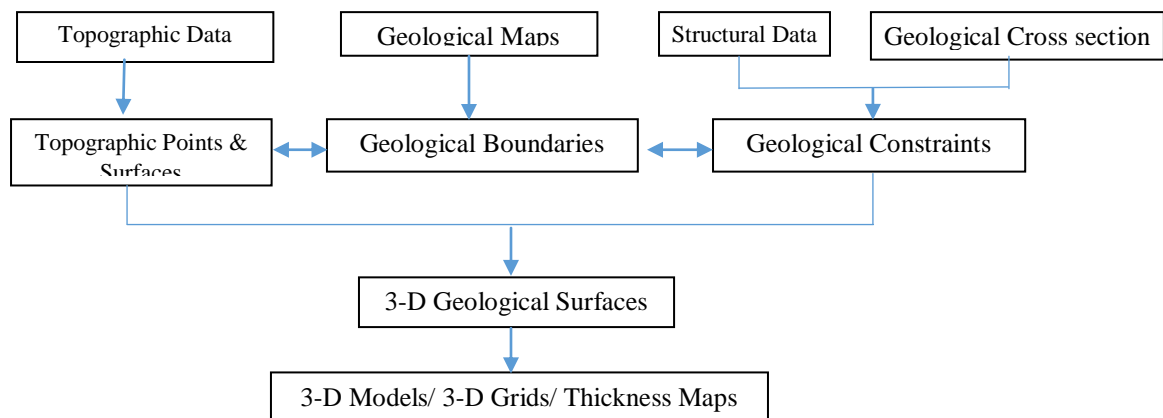


Fig.3. 3D modelling through data integration between GIS and GoCad.

After having imported the available information into GoCad, the following steps should be performed:

1. Construction of the topographic surface by interpolation of points;
2. 3-D mapping of the linear geological boundaries and linear features by vertical projection on the reconstructed topographic surface;
3. Definition of geometrical constraints from planar and linear outcrop data; Construction of a network of cross-sections based on field observations and geometrical constraints;
4. Creation of 3-D surfaces, closed volumes and grids from the constructed objects. The methodology demonstrates that although only outcrop data were available, 3-D modelling allows the checking of the geometrical consistency of the interpretative 2D sections and of the field geology, through a 3-D visualization of geometrical models.

#### **4.3 Application of 3-D GIS with Lynx geoscience modelling system**

3-D GIS provide the tools for enabling interactive construction of volumetric models of the ground profile. 3-D modelling system for ground engineering [13], is discussed. This permit analysis and interpolation of geological characteristics, facilitating appraisal of the engineering problem.

The geometrical modelling of the ground is based on cross-sections derived from the geological map, boreholes and CPT soundings. The Lynx geoscience modelling system has been used for the modelling tasks. Using Lynx, data is stored in a 3-D database projected to user-selected planes to delineate polygonal boundaries of each geological unit. These are connected by links to form solid volumes.

##### **Example 1: Foundation Selection**

1. The 3-D geotechnical model is constructed, as a continuous distribution utilizing grid cell. This grid is intersected with the volume model of soil units to provide the data structure suited to spatial analysis and geotechnical characterization. The 3-D grid data structure supports the geological controls on the interpolation and calculation routines and provides a continuous distribution of the parameter of geotechnical interest.
2. Using the geostatistical modelling routines in Lynx, the distribution of modelled parametric values (such as cone resistance values) within the modelled volume may then be predicted. The prediction is made using ordinary volume kriging on log-transformed sample values.
3. The total settlement is a direct result of the subsurface geometry and the geotechnical properties of the soil masses. The vertical displacement is calculated at the mid-height of the compressible layer (the centre of the 3-D grid cell). By adding the individual displacements from bottom to top (3-D grid column), the total settlement at any depth is obtained. The 3-D settlement may then be calculated at the centre of each cell by applying a volume weighted average algorithm.

##### **Example 2: Tunnels**

1. Two main sets of cross sections were drawn to define the geological unit boundaries, aided by fence-diagrams linked to form a solid volume model. The accurate volume modelling had decisive impact. The inclusion of geological semantics facilitated provision of technical advice delineating each unit's polygonal boundaries.
2. Geotechnical modelling was based on the site investigation data and the results of laboratory tests on soil samples. The data scarcity restricted the use of geostatistical interpolation as an option. In most instances, the assignment of geotechnical parameters was done by using a knowledge-based system (preferences and rules).

#### **4.4 Applications of 3D-GSIS with Lynx-GMS**

Three-dimensional modelling technologies collectively identified, as Geoscientific Information Systems, (GSIS) - have been developed to address the need for a precise definition of subsurface conditions. Case study of Interactive volume modelling for geotechnical modelling of tunnel intersection in soft ground is discussed [4]. Applicable for checking feasibility and engineering analysis, may be used for production estimation and model based simulation with a link to knowledge-based expert systems of TBM tunnelling. The requirement was to check the influence of the site geological and geotechnical conditions on TBM performance in soft soils. The methodology consist of following steps,

1. Developing parallel longitudinal profiles, to delineate the geological boundaries by interpolating CPT database.
2. Development of the volume elements through a boundary-matching algorithm applying a linear interpolation between the different lithological components at a common plane between the different longitudinal sections.



3. A multi component interactive modelling approach to account for pinching-out or bifurcation of lithological units.
4. The Tunnel geometrical model using the map data structure based centreline design approach in Lynx-GMS
5. Generation of new volume components from the volumetric intersection between subsurface volume model and the tunnel geometrical model using an optimized intersection algorithm. The intersection results in identification of the lithologies within the tunnel route and the volumetric quantities are reported for each intersection component.
6. Geostatistical modelling for property distribution and prediction of the spatial variation of relevant variables, based on sample information. Also allowing spatial analysis of the interpreted and predicted information in terms of volumetrics and visualization procedures. The interpolation techniques using different mathematical (Kriging) algorithms, operating on 3-D grid model.
7. The 3-D-block model is used to estimate volumes, volume associated geotechnical variables, and their spatial variation.
8. Statistical and spatial data analysis to achieve the property (parameter) distribution for each unit within the grid cell centroids ensuring data integrity.

#### **4.5 Model Vision or GMSys, SKUA, GoCad, and Geomodeller.**

Geoscience Australia and GeoScience Victoria uses modelling package which consist of Model Vision or GMSys, SKUA, GoCad, and Geomodeller [1]. The workflow with the combined use of this software consist of the following steps:

1. Integration of all available surface mapping, drilling constraints, potential field data sets, 3-D inversion models, seismic data, and other 2-D and 3-D data sets into a 3-D storage and visualization environment.
2. Defining an agreed upon stratigraphy for the model region. Construction of serial cross sections based on surface geology and geophysical constraints perpendicular to major structural trends with some tie sections parallel to trend.
3. Digitization of serial cross sections into a 2-D/3-D/4-D potential field by forward modelling package such as Model Vision or GMSys. These programs allows the measured potential field response of the section to be compared with the calculated response for the interpreted section based on the geometry and rock properties assigned. Although the cross sections are essentially 2-D, the 2-D/3-D/4-D forward modelling algorithms allow the strike of the geology to be at an angle to the section (i.e. not perpendicular) and allow bodies that terminate out of the plane of the model to be included and contribute to the calculated signal. Forward modelling of this type allows a first-order assessment of the validity of the starting geometry.
4. Use a combination of implicit and explicit modelling methodologies (primarily SKUA, GoCad, and Geomodeller). Implicit modelling (e.g., SKUA, Geomodeller) requires that contacts and observations are assigned geological types and are placed within a defined stratigraphic column. The model is then constructed from the constraining data by the software and respects the defined relationships.
5. Run 3-D potential field inversions on the model (or its individual parts), ensuring that the 3-D geological model is consistent with the available geophysical data sets. These inversions can highlight regions where the model's predicted potential field response varies from the measured data. The results of these inversions are fed back into the modelling workflow, further enhancing the model.
6. Visualize the modelling, primarily done using GoCad, where the model constrains serial and seismic sections, and any other appropriate data sets and surfaces are visualized and analyzed.

#### **4.6 Multiple Software Packages for Addressing Geological Complexities**

Following are the Methodologies Used for 3-D modelling (Sedimentary Basin modelling) by French Geological Survey (BRGM) using Multiple Software Packages for Addressing Geological Complexities [3]. The commonly used software are,

1. Petrel (Schlumberger) and EarthVision (Dynamic Graphics) for simple geology and basin analysis;
2. Isatis (Geovariance) for studies that need geostatistical analysis and quantification of uncertainty to assess resources;
3. Surpac (GemCom) for mining projects that require construction of 3-D geological models for assessment of resources;
4. 3-D GeoModeller (BRGM-Intrepid Geophysics) for helping to define complex 3-D geology based on implicit modelling of surfaces; and
5. MultiLayer/GDM (BRGM), which is especially suited for data control and for layered models where traditional geostatistics is particularly efficient.

The procedure for Shallow Subsurface modelling by BRGM include following generalised steps

1. For 3-D models, the BRGM defines a lithostratigraphic table (stratigraphy) and specifies the type of contacts between various units (e.g., conformable, on lap, or eroded), and faults are considered as vertical objects.
2. Kriging methods are used to calculate 2-D lithologic surfaces (top, base, and thickness) using geological maps, borehole information, and vertical faults system. By considering lithologic relationships, 2-D surfaces are organized so that they build 3-D layered geological models.
3. To assigned the material properties to the model, stratigraphically interpreted boreholes are used to perform the final 3-D stochastic simulations and to fill the model with lithologic and petrophysical properties by taking into account models of the sedimentology, facies, and the geostatistical methods described.. The stochastic geostatistical techniques used to fill 3-D models are sequential Gaussian simulations (SGS) and sequential indicator simulations (SIS) (Goovaerts 1997) which allows uncertainty to be estimated.

## **V. Future Scope**

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

1. The 3-D modelling process should be highly integrated to enhance links between modelling software packages, databases, GIS simulation software, and 3-D viewers [3].
2. 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[13].
3. The major problem experienced concerned the data exchange, between the 3-Dmodelling and FEM packages. The number of nodes in the exported file was too high for the FEM package to effectively generate a finite element mesh. In addition, the thin layers and lenses modelled in the 3-D system could not be regenerated in the FEM geometry especially when the length to depth ratio of the section is high[13].
4. Finite Element modelling (FEM) enables surface or volumetric representation through the use of 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 [13].
5. Robust data management tools are essential when transitioning from regional to more site-specific investigations.[7].
6. Over time, common data formats and relevant standards should emerge, leading to increased interoperability and exchange [7].
7. There is need to establish the value of standards for 3-D geological mapping and modelling[7]. Which will be helpful to, evaluate the perceived benefits of various standards, and prioritize the standards.

## **VI. 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 [5]. Therefore, the methodology workflow steps discussed in the literature for different case studies ensured the success of the 3-D integrated geological models at specific study sites only, they should not be thought of as a standard, but rather as guides that other users can follow or modify. The selection of particular software & modelling approach need to refine based on the needs and the resources available. 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.

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