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An Overview of 3-D Geological Modelling Part II. Summary of Major 3-D Geological Modelling Methodologies

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Abstract: The paper present an overview of the 3D Modelling Methodologies in the context of research and modelling practices. Various software environments are available for Modelling, corresponding methodological workflows and their combinations for 3-D geological Modelling can be performed based on the availability of data and the objective of the modelling. The GSI3D-methodology and Geostatical Modelling Techniques are discussed and mutually compared in detail including their relevance & limitations. The methodological modifications such as Multisource Data Integration, Coupling Methodology, and Modelling for the Geological Structure of the Sedimentary Basins, develop to overcome the shortcomings of earlier approaches are discussed. The model validity and associated uncertainties of 3-D Modelling are discussed in the simplified way. The Future trends for research and development in the area are also highlighted.
Keywords: Geostatical Modelling Techniques, GSI3D, Uncertainties in Modelling

I. Introduction

A series of sophisticated 3D Modelling techniques have been developed to build 3D structure models from different types of data. The methods available are, the Horizon Method for generating 3D solid models of geologic structures from borehole data, the Borehole-Surface- Solid Method to construct discontinuous surfaces in sedimentary stratigraphic systems and 3D Property Modelling by applying automatic interpolation algorithms or geostatistics methods (various Kriging interpolation). Approaches to geological Modelling are different to suit the needs of individual geological survey organizations (GSOs), which will likely remain the case in the near future. Convergence or streamlining of software use might occur over time, but it is difficult at present to envisage a standard piece of software, as this will intrude into individual organizational policies and culture, as well as the possible capabilities of clients [11].

The initial methods developed for Modelling consist of mathematical algorithm based Geostatistical Interpolation Method and cognitive, knowledge based GSI3D method. Further specific need based Modelling leads to development of alternate approaches, addressing the limitation of the basic methods. Subsequent work discuss the various aspects of these methods.

II. GSI3D Methodology and Workflow

GSI3D is being used by the British Geological Survey (BGS) on different mapping scales, in combination with GoCAD for deep subsurface investigations, geological Modelling and for regional investigations of groundwater-contaminated mega sites [26]. GSI3D is based on a ‘‘constructive method’’ and allows the implementation of different additional geological 2D information. This ‘‘knowledge-driven’’ approach is based on the detailed information of the sedimentological and stratigraphical situations. GSI3D allows the Modelling of the distribution and geometry of sedimentary layers by Knowledge based control of the modeller. The GSI3D-methodology and the respective software-tool can be used for the data visualization, processing, analysis and Modelling application [16].

The procedure for producing 3D model with GSI3D can be summarized as follows,

1. The Modelling process with GSI3D is based on the creation of a series of intersecting cross-sections. Regularly spaced intersecting cross-sections are combined to build a fence diagram. This series of regularly spaced user-defined, intersecting cross-sections should cover local variations, anomalies and should incorporate linear bodies, other cut-and-fill structures, not adequately included in the major cross-sections [26],[6]. The down-the-hole data are used to build up this net of consistent cross-sections, defining the spatial distribution as well as top and base of each geological unit. Drill-logs, digital thematic maps topographical, geological, hydro-geological maps are used for detailing [16]. The software allows the input of geological 2D mapping or surface information, especially from areas with a less dense borehole record [26].

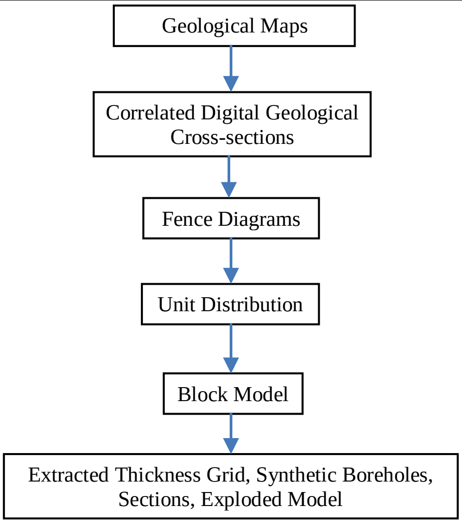

Fig.1.GSI3D Workflow

2. The geological units are defined according to their lithological and stratigraphical characteristics, considering their genetical and morphological perceptions. This mesh of consistent cross-sections defined the lateral distribution and thickness of each unit present and covers the genetic aspects of landscape evolution envisaged by the geologist [16]. Thus intersecting network of correlated cross-sections are created for model, precisely embodying the geologist's interpretation in the context of the local geology [1].
2. The generalized vertical section are created.DTM of appropriate resolution is loaded. Borehole log data are stratigraphically, lithologically, and, or geophysically coded at the base of a generalized vertical section. Boreholes for cross sectioning are selected. Starting with the shallowest, geologically realistic lines are digitized to connect the geological units [26],[6].
3. The distribution of each unit can be displayed and used to digitize distribution envelopes for individual geological units. These envelopes define the sub-crop /outcrop that is used for Modelling. The positions of geological boundaries at cross-section intersections are checked and modified as necessary. An iterative modification and fitting of intersecting cross-sections allows the generation of reasonable geological subsurface structures [1]. The complete and mutually consistent cross-sections are used in the software to interpolate surfaces between them [1].
4. Once the distribution and base of each geological unit has been defined in the cross-sections, these 2D correlation lines are triangulated into unit distributions, giving the lateral extent and the depth of the base of each geological unit [16], i.e. the 3-D spatial model is calculated by triangulation that interpolates between the correlation line nodes in sections and along geological boundaries. This produces a series of Triangulated Irregular Networks (TINs), for each rock unit modelled [12], [13]. The process also counts for the location of interface, dip, direction, and other data to produces a 3D implicit function representing a solid model [24].
5. The 3D geological model is stacked by attributing to each surface by reference to the DTM [26], [6]. Volume bodies of each geological unit are subsequently calculated by stacking the base of each defined unit to the base of the covering unit. This also generates the thickness of each geological unit as well as the elevation of its upper surface. Volume body calculations commence from the youngest unit downward, where the Digital Terrain Model defines the top of each outcropping unit [16].

The initial procedure requires no prior knowledge of the structure. It can be useful to construct an initial 3D model as if no faulting is present, to avoid the model being unduly influenced by preconceived ideas about the local structure [1]. Cognitive GSI3D Modelling methodology allows modeling the distribution, geometry, and thickness of geological units by using the modelers' geological knowledge, to pick out areas of faulting and generalised the faults into a coherent fault network [20]. If the presence of faults is inferred, they can be introduced at later stage in the Modelling to explain the data anomalies, and where they could be justified by the data. Some unexplained anomalies may indicates additional faulting which needs sufficient data to confirm the position and orientation with confidence [1].

The model can be checked for miscorrelations by creating a rectangular grid across the whole area, manually viewing the ''synthetic'' cross-sections, and correcting as necessary [26], [6]. Further verification of the constructed unit distributions obtained from the structure-model, can be done by comparison with field data.

Expected outcrops and subsurface unit boundaries can be exported from the 3D model to verify and modify directly from the field data. The field verification improved the accuracy of the 3D structure-models constructed from gathered archive data sets [16].

III. Geostatical Modelling Techniques

Geo-lithologic data often have different origins (directly or indirectly collected), different times, methods and techniques of acquisition, with different degree of details and descriptions. A good geological interpretation depends on data quality, the degree of detail, and data comparison. Low quality or poorly comparable data can only generate barely reliable results despite the use of the most efficient processing methods.

The lithologic data derived from subsoil investigations, along with the data management and integration forming geodatabase can be used to construct a 3D geological model applying geostatistics [10].

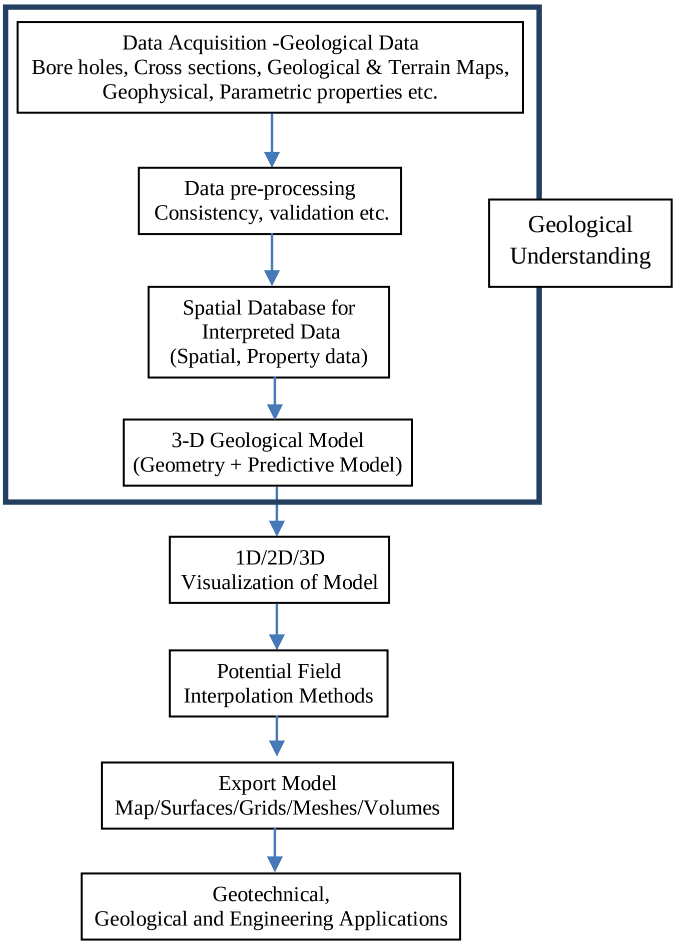

Fig.2.Geostatistical Modelling Methodology

Geostatistical Modelling can be performed for property distribution and prediction of the spatial variation of relevant variables, based on sample information [8]. The model can integrate GIS (spatial database) and 3D geostatistical methods to predict variation of soil/rock properties. Within the model, geotechnical variables are generated using 3D geostatistical methods with a measure of reliability, making it possible to use the estimated results more efficiently within the GIS database. Geostatistics provides a tool for analyzing spatial data and estimating unknown values. Managing 3D geoscience data structures includes 3D information and corresponding attributes such as lithology, stratigraphy, and rock quality [5].

The interpolation techniques used consist of different mathematical (Kriging) algorithms, operating on 3D grid model. Statistical and spatial data analysis to achieve the property (parameter) distribution for each unit within the grid cell centroids ensuring data integrity. The interpolation methods are not physical Modelling tools, as they do not have direct correlations with real-world physical processes. 3D geostatistical analysis uses volume representation methods (voxels). Where the 3D interpolation randomly converts sampled data to volume data [10]. This 3D-block model is used to estimates of volumes, volume-associated geotechnical variables, and their spatial variation [8].Construction of a 3D 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. Based on a specific geostatistical interpolation procedure, the Geological Editor interpolates the local input data to the whole 3D space to build a regional-scale 3D geometrical model. The reference boundaries of lithostratigraphic units, from the geological maps, locally modified from the boreholes data allow to constrain the interpolated surfaces, and to limit the interpolations to the zones of different units. Construction of the digital model involves interpolation of the parameters at the nodes of a regular grid through kriging. This interpolation allow calculating the level of the formation and their thickness. Compared to other methods of automatic interpolation, kriging has the advantage of associating an estimation error with each estimated or interpolated value. This error is used to plot iso-uncertainty curves thus providing a measurement of the precision associated with the interpolated parameter at any point on the map [23].

Along with the Geological knowledge (surface geology), the geophysical imagery (gravity data, and a deep seismic reflection profile etc.) can be combined at the crustal scale to model the 3D geometry. The model showing internal geometrical consistency, compatible with available geophysical data (seismic and gravity), and integrating the geological knowledge at a regional scale can be prepared [15]. The 3D geometrical model is built in a geo-referenced system; with 3D integration of a DEM, a simplified geological map (lithological contact information), accounting foliation dips measured within the different unit local gradient information and gravity cross-sections. To compute the 3D 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 can be used to constrain the geometry of the structures at depth. The geometry of the lithological boundaries can be adjusted performing 2D gravity modelling along the geological sections. In the next step, integration in the 3D geometrical modeller produces consistency between all cross-sections and the geological map. In the model, lithological units are volumes to which physical properties (density, susceptibility) are attributed. Finally, using the densities reported, the 3D gravity contribution of the resulting 3D model is computed and compared with the Bouguer anomaly. When discrepancies between computed and observed gravity fields are identified, the geology can be locally reinterpreted, the model being interactively adjusted in 3D. The 3D 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 [15].

IV. Comparison of GSI3D and Geostatical Modelling approaches

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, GSI3-D, 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. To elaborate the comparative merits and demerits of Geostatistical based 3D Modelling approaches, and constructive cross-section based interpolations of complex sedimentary successions are compared in their results and suitability with the case study, High-resolution 3D spatial modelling of complex geological structures [26]. The details of the case study are as follows.

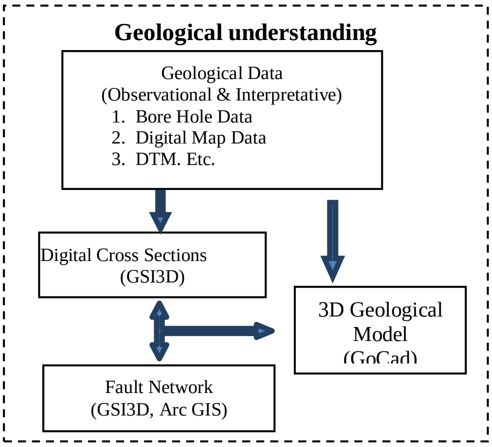

Fig.3a. Workflow for combining numerical and cognitive 3D Modelling approaches

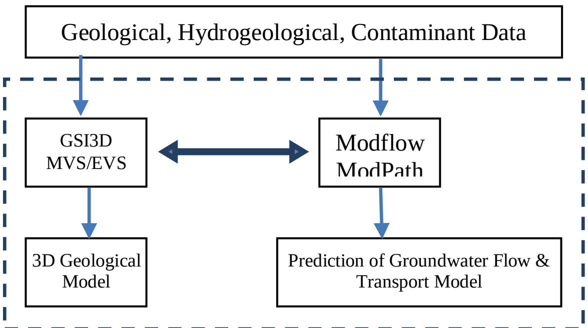

Fig.3b. Conceptual Flow of 3D Model

The spatial model includes point data such as borehole data (lithology/stratigraphy), hydrochemistry (contaminants) monitoring data, line data such as rivers and creeks, and polygon data and surfaces such as the open pit mining areas. Conceptual method consist of GIS-based ‘‘Spatial 3D-Model’’ with emphasis on 3D geological Modelling and prediction of groundwater flow and transport for an integrated environmental risk assessment. The GIS data management for all hydrogeological and hydro-chemical data was done with ArcView (ESRI). The geological cross-sections with their vertical 2D structure were held in a special tool for geological 3D models. The geological structure had to be held in a GIS database to obtain an interface to numerical groundwater Modelling tools such as Feflow or Modflow. These data are stored in GRID or point formats in ArcView.

The Modelling work with GSI3D using a ‘‘constructive’’ and knowledge driven approach, is compared with 3D Modellingbased on a geostatistical interpolation with the Modelling system EVS/MVS (Environmental/Mining Visualization System) using the identical data set. The EVS/MVS is based on the geostatistical interpolation between boreholes and calculates the contouring more or less automatically. EVS/MVS (C Tech Development Corp. Kaneohe, HI) provides true 3D volumetric Modelling and 2D and 3D kriging algorithms with best fit of variograms to analyze and visualize geo-scientific and environmental data. The result with EVS/MVS, exclusively based on drilling information and geostatistical interpolation.

The 3D geological Modelling system and the GIS database are used for further data processing to adapt the geological model to the structure of a numerical groundwater model. The hydro-geologically simplified 3D geological model also serves as a database for a numerical groundwater model. The adaptation of the 3D geological model data to a 3D numerical groundwater model is possible, but it has to be corrected to avoid structures with fading out layers and to aggregate geological units with similar hydro geological characteristics.

The lithostratigraphic approach in construction of 3D geological models gives better results than only a pure grain- size or lithological-based automatically contoured approach. This statement is valid for most Quaternary sediments and artificial cut-and fill structures. The major challenges in regional 3D Modelling are the geology data verification and the interpretation of complex geological sequences, in regional stratigraphy. Without the knowledge of lithostratigraphy and facies relations, any 3D Modelling will be incomplete or will fail.The assessment of the relative uncertainty in the form of uncertainty interpolation (red mesh - high uncertainty, dark blue mesh - low uncertainty) by Colour-classified mesh of the uncertainties of the upper surface is based on the borehole data and on the spatial variability of the z values, calculated by EVS/MVS. 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 [26].

V. Alternate Modified Approaches.

The various available data type, modelling objectives, engineering applications are the important factor which influence software selection. The required software functionalities may not be included in single software, making it essential to use more than one software in combination. However the specific case study may need the alternate approach to deal with, customized requirement or the limitations of the existing methodology or software. Few case studies, which address the alternative methods such as Multi-Source Data Integration Techniques, Coupled Modelling, and Stratigraphic Modelling, are discussed, to cope with limitations of existing approaches. These Alternate Modified Approaches also highlights the ongoing research & development in the field of modelling.

5.1 An effective method for 3D geological Modelling with multi-source data integration.

Density of data greatly affect the geostatistical interpolation method. Effective integration of all available multisource data can improve the modelling [25]. The case study proposes a stepwise refinement method with multi-source data integration and present a comprehensive yet convenient 3D Modelling system. The method can naturally simulate geological structures irrespective of the quantity of available geological data.

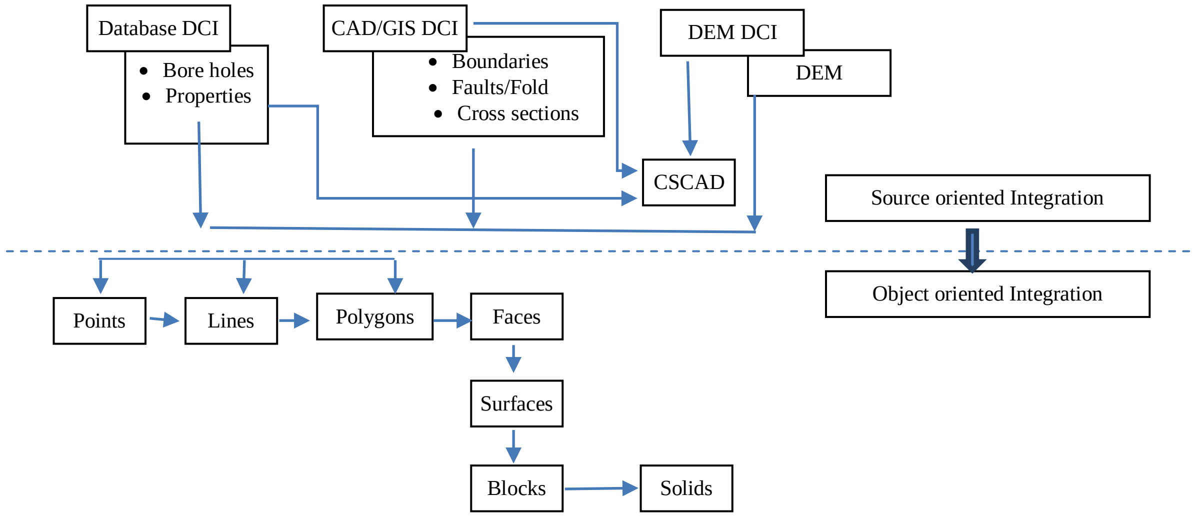

Fig.4. Integration Architecture

Uncertainty and inaccuracy caused by sparse original data cannot be improved by interpolation methodology only. The paper, proposes a method for 3D Modelling with multi-source data integration. It suggests stepwise refinement on multiple data and mathematic means for increasing the accuracy of 3D models gradually and effectively. Thus simulating geological structures irrespective of the available quantity of geological data and the accuracy of the model could be significantly improved. Furthermore, the most significant feature of horizon Modelling presented is that the strata boundaries can be precisely controlled with multi-source data integration.

1. The method consist of developing a 3D subsurface visualization system (SVS). An efficient and robust algorithm for fault simulation based on the properties of faults has been developed in SVS.
2. To utilize the geological data of different types and qualities and to maintain the data consistency, data Integration architecture has been design. It involves source-oriented integration and object-oriented integration. The source-oriented integration offers interoperability of various data sources with ability to store, process, display and manipulation in the same coordination system. The aim of data conversion interface (DCI) is to realize the integration of heterogeneous geoscientific data and to guarantee the integrity and consistency of these data accepted by SVS. Database DCI is used to convert direct data, such as boreholes and all kinds of property data. The indirect data integration, consist of digitization and its conversion to SVS using CAD/GIS DCI or interpretative software. The SVS offers a cross sections CAD (CSCAD) tool, to semi-automatically define a cross-section based on direct data, indirect data and related geological information and to perform simpler and more accurate analyses. Supplementing cross-sections by a CSCAD tool is a simple and powerful way of filling the sparse data gap. CSCAD access digitized geological data, a topographic line and faults line are deduced, and then interactively defines the location of the cross-section to generate stratigraphic boundaries.
3. Object-oriented integration is implemented by building a hierarchical link list, which is used to store topological and geometrical information of objects. The available geological data by source-oriented integration is ultimately stored in the point link list to form the base-class objects for object-oriented integration. Fault simulation is perform to describe the spatial distribution of the fault deduced according to the properties of the fault line Thus constructing the TIN model of faults.
4. Horizon Modelling can be performed using a stepwise refinement of 3D Modelling that makes the accuracy of the horizon model to be gradually and effectively improved with data such as boreholes, cross sections, geological maps, topographic maps and structural geology maps.

5.2 Coupled Modelling between geological structure fields and property parameter.Scope of the Coupled Modelling methodology [28].

The current Modelling techniques are useful for visualization of geological structures or property parameters independently, but are not the coupling relationship among different data fields, limiting the reliability for quantitative spatial analysis and professional applications. The geological structure fields represent the spatial distribution patterns of geological bodies, and control the spatial variation of the property parameters within individual geological units. Either independent Modelling" or "sequential Modelling" process does not consider the coupling relationship in geological genesis and characteristics between geological structure fields and property parameter fields resulting in the Modelling frequently differ from the actualsubsurface conditions.

The method, present Modelling framework for the coupled Modelling and analysis of geo-objects in 3D engineering geological space. This coupled Modelling framework is well suited to produce detailed 3D geological models attributed with physical, chemical, engineering or hydrogeological parameters, and intuitively analyze property characteristics within each modelled unit and their spatial relationships in 3D.

There are three innovative improvements in the coupled Modelling framework

1. **3D spatial data model**
   The mixed 3D spatial data model, which is a combination of boundary representation (BRep) and Geocellular, is designed to address the need for the unified description of geometry and topology of geo-objects as well as their internal properties.
2. **Reconstruction method for property parameter fields**
   To obtain geologically reasonable property models controlled by geological constraints, the qualitative geological constraints are converted into quantitative control parameters in data preprocessing stage, and different property interpolation schemes are used respectively to handle different types of geo-objects. The spatial interpolations/extrapolations between sampled property data points, guiding by the quantitative geological interfaces, can be carried out.
3. **Generating mechanism for coupled geological models**
   Finally, to gradually refine 3D geological models, the iterative Modelling technique is imported, and an efficient mechanism for information feedback and error correction is set up.

5.3 Modification in modelling methodology for the geological structure

The Morphology and geological history of specific formation can be considered in Modelling process to form geologically and topologically correct model. The corresponding adopted methodology should be

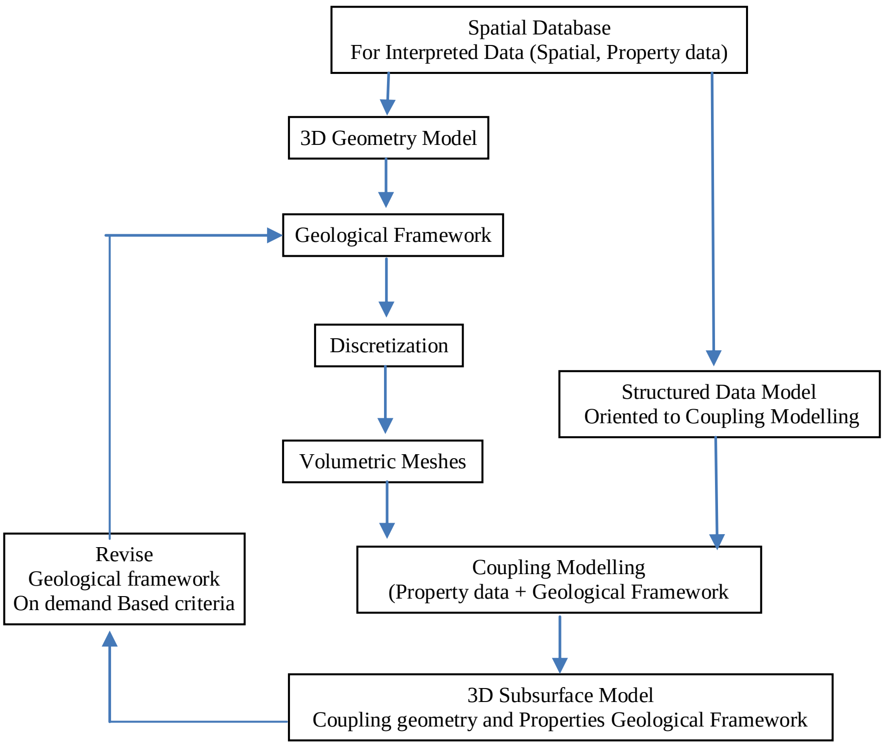

Fig.5. Coupling Mechanism

modified to respect the peculiarities of the geological formation. The following two case studies included highlights the need for adoption in methodology to count for geological understanding especially for stratigraphic Modelling

The first case study of Three-dimensional geologic modelling of the Santa Rosa Plain, California [7].covers the methodology for stratigraphic Modelling.

1. Assignment of stratigraphic tops was fundamentally lithology based and, as such, was rock-stratigraphic rather than being a true stratigraphic assignment based on timelines or sequence boundaries. Mappable lithologic sequences were identified in well data by analyzing numerous serial cross sections across the study area and making stratigraphic interpretations based on rock type, bedding and sorting characteristics, stratigraphic succession, and an understanding of the relationship between the mapped geologic units and their lithologic characteristics.
2. Stratigraphic tops were picked interactively by viewing lithologic logs wells in a profile. Contacts were picked in an iterative fashion from numerous cross sections of varying orientations with combinations of wells examined to eliminate spurious picks and maximize the consistency of the stratigraphic interpretation.
3. The resulting model was trimmed at the top using a digital elevation model (DEM) to represent land surface elevations and at the base by a grid of the top of the geophysically modeled high-density geophysical basement. For the 3D lithologic model, strata were assumed horizontal. The assumption of horizontality is likely more valid for the younger, upper parts of the basin fill than for the deeper parts of the alluvial section.

The second case study of comprehensive approach to the 3D geological modelling of sedimentary basins [19], is discuss the methodology to overcome limited data coverage.

1. The Modelling approach is based on developing the algorithm of the main geological processes to automatically define the geometrical relationship is defined between model elements. The algorithm is based on the assumption that sedimentary basins are formed as a result of the repeated sequence of sedimentation, faulting and erosion. Assuming that the tectonic deformation occurs in sequential cycles and each subsequent tectonic stage stratum is separated by a regional unconformity.
2. This is done by reconstructing the thicknesses of original layers before erosion and after that by slicing them along known fault lines and applying known fault displacements to all the layers within each tectonic stage. Therefore, an applicable layer thickness is adjustable by taking the amount of erosion by the presence of regional unconformities into account. The method can be applied if stratigraphic intervals from boreholes of the whole geological section and data describing fault locations and displacements are available for at least one surface within the tectonic sequence.
3. By applying constant thickness to the sedimentary layers it is possible to automatically estimate and allocate the extents of the layers and fault structures keeping consistencies of the missing and adjoining strata. It allows extending viable topography of each layer outside the area described by data where layer extents are defined in the intersection with the overlying sequence. In the presence of known faults, the displacements along them are automatically transferred to adjacent layers.
4. The methodology used allows testing alternative interpretations of the chronology of geological events. This approach allows of successful Modelling of the geological structure of the sedimentary basins with limited data coverage: stratigraphic intervals from well logs describing the thicknesses of sedimentary strata and a limited amount of structural data. Sedimentary layers are handled by Modelling assuming non-eroded thickness distribution and using geometrical adjustment from the known fault displacements. As a result, geometrical relationships of the model layers are deduced automatically in the presence of unconformities.
5. The developed 3D geological model highlights coherent interpretation of the geological and structural setting. The extents of the modelled layers overcome limitations of interpretations stored in maps. The neglected areas in map data are reinterpreted by grounding them on known surrounding borehole data and contain geologically and topologically legitimate interpretation.

VI. 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. A good conceptual engineering geological model should be capable of anticipating most of the engineering geological issues that could potentially affect the project [18].

3D model building based on the surfaces is tedious and time consuming, and impossible where the geology is complex or discontinuous. To overcome the drawbacks, a measure of certainty (confidence level) can be assigned to the user-interpreted boundaries. This sort of functionality allows the user to incorporate his belief regarding the model [17].

"Reference [6], 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

To quantify uncertainty, the causes of uncertainty and the relationships between the causes should be identified. This can be done by using a cause and effect diagram known as an 'Ishikawa' (after its inventor) or 'fishbone' diagram. Once identified the causes of uncertainty, it is then necessary to quantify it in a way that can be simply understood and applied by users. For a geological surface produced by gridded interpolation of borehole data, one method for estimating the uncertainty produced by the gridding procedure is to resample the (borehole) data used to interpolate a gridded surface many times (known as 'bootstrap' resampling). Every time interpolating a new surface, and measuring the standard deviation at each gridded point resulting from the interpolations. The predicted uncertainty can be expressed using resampling methods. Further research is needed to develop means of presenting and visualizing overall uncertainty (and its variability in different parts of a 3D geological spatial model). In similar way, several simulations can be carried to compute the probability for each grid cell of the various lithofacies and petrophysical properties. These probabilities can quantify the uncertainty of the 3-D volume model [3].

According to reference [4] Progresses in geomodel representation, construction and restoration can never remove ambiguity present in subsurface data. In many cases, creating several possible models reflecting the uncertainty is therefore preferable to building one single best model, which tends to smooth features in areas of high local uncertainty. This smoothing effect is often non-realistic, and may lead to significant biases in the Modelling output (e.g., simulated behaviour of an aquifer or hydrocarbon field). Multi-realization approaches better reproduce realistic geological features and assess the impact of subsurface uncertainty on Modelling response.

The Modelling of subsurface geometry should further evolve beyond pure data fitting approaches by integrating geological concepts to constrain interpretations or test their consistency. Also, instead of striving for one single best model, it is appropriate to generate several possible subsurface models in order to convey a quantitative sense of uncertainty. Depending on the Modelling objective (e.g., quantification of natural resource, production forecast), this population of models can be ranked. Inverse theory then provides a framework to validate (or rather invalidate) models which are not compatible with certain types of observations.

As per reference [9], Primary limitations of 3-D models are caused by uncertainties that are propagated throughout the model. The main sources of uncertainties that influence 3-D models are:

i. **Data distribution:** Irregular or sparse data distribution can result in less meaningful regional interpolated values. Wider the scattering of the known values, more difficult and less precise it becomes to estimate what lies between them.
ii. **Interpolation method:** The resulting value varies, depending on the chosen interpolation method (e.g., less subjective for alteration zonation and trend definition).
iii. **Chosen criteria or constraints:**A wide variance of results can be obtained by choosing different queries because the user's subjectivity is involved. It is important to note that data density is one of the most crucial factors in generating targets.

As per reference [2], the uncertainty of 3-D geological models is not only restricted to the data and algorithms of the model, but also involves the geological inferences and interpretations that can be used for the final models. The Modelling uncertainty in geological models relied on geostatistical models and assumptions that were often violated when the real geology became complex.

If the data density is high, then the uncertainty is lower (or vice versa), and if the geological complexity is low, then the uncertainty is lower (or vice versa). The empirical uncertainty obtained from this approach can be calibrated into either an estimated absolute uncertainty or a relative scale using expert judgment.

To calibrate the uncertainty the expert provides three pieces of information:

i. The estimated absolute uncertainty of the surface at the borehole (i.e., the uncertainty in depth in the log);
ii. The estimated uncertainty on the surface where least information is available; and
iii. The distance from the borehole up to which the surface can be predicted confidently (the radius of influence of the borehole).

Example to count uncertainty due to measure data density and geological complexity are elaborated by [14]. The uncertainty was represented as Uncertainty assessment of drill locations and drill type, and a grid of the average assumed error for geological surfaces. The study concluded that the results agreed with intuitive expectations for the uncertainty, but that drilling should be undertaken to validate the uncertainty assessment of the model. [14]. The Illinois State Geological Survey (ISGS) recognized the impact of four factors that contribute to uncertainty in geologic maps: Variations in data quality, Variations in data density, Generalizations in texture, and Generalizations in thickness. The contributions of these factors to map uncertainty were evaluated with respect to terms of their likely impact on the predictive accuracy of a regional groundwater flow model that would use the 3-D geologic map. The errors in thickness interpretations were dependent on data density, data accuracy, and the underlying complexity of the geologic deposit being mapped.

All three-dimensional geological models (and all 2D maps as well) are associated with uncertainties, which can result from, but are not limited to, the factors such as Modelling software, The expertise used for interpretation of the geology and hydrogeology and the software users [21].

Reference [14], define and tested the method to quantify the uncertainty associated with geological surfaces in a 3D model. Kernel density smoothing and resampling of borehole locations along with expert-user interaction are utilized to provide an estimate of the uncertainty in a geological surface due to data quality, data density and geological complexity. The method aims to demonstrate a semi-quantitative uncertainty estimation procedure for 3D geological models that identifies all sources of uncertainty, both qualitative and quantitative.

1. With increasing radial distance from the borehole, uncertainty in the position of the geological surface increases. This process can be modelled by setting a Gaussian function centred on the borehole, and the 'radius of influence' of the borehole (i.e. the standard deviation of the Gaussian distribution) can be controlled by changing the variance of the Gaussian function. Kernel density smoothing can be used to estimate the uncertainty from more than one borehole by adding together the Gaussian outputs for each borehole. This procedure can be extended into two dimensions. The sum of these Gaussian functions is an alternate for uncertainty, where high density represents low uncertainty and low density leads to high uncertainty.
2. The data density method can produce an estimated uncertainty grid for each of the types of investigation method (viz. sonic boreholes, excavator, and cable percussion.). The results from this can be compared at each point on the interpolated grid and, using the lowest uncertainty of the three at any given point, can be combined to produce an uncertainty estimate that takes into account both data density and the data quality. In areas where there are rapid changes in depth over a relatively small area (i.e. more geologically complex areas) a higher density of boreholes is required.
3. The uncertainty arising from changes in complexity over a surface and its relationship to boreholes can be estimated using a computer intensive iteration approach. Resampling the xyz coordinates of geological surfaces in boreholes and fitting a surface to the resampled borehole coordinates on a given grid. The process were repeated several time recording the surface positions on the interpolated grid for each iteration. Measure the 95% confidence limit on the interpolated depths on the grid obtained for each iteration, to give an estimate of uncertainty.
4. The identified factors contributing to uncertainty (geological complexity, data density and data quality) were combined by adding the square root of the sum of the squares of the sources of uncertainty to produce an overall uncertainty for the modelled surface. This empirical approach produces a combined uncertainty that fits with the intuitive expert judgement rules and allows prediction of uncertainty at any point on interpolated surface.
5. Given that the uncertainty model for a given surface uses the xyz coordinates of the boreholes or other raw data points and some expert judgement, it may be possible to use these inputs and the uncertainty output as an 'expert system' to predict uncertainty in other situations without the intervention of the expert. Adaptive Neuro-Fuzzy Inference System (ANFIS), of the MATLAB can be used for this automated system for estimating uncertainty. Where acceptable agreement between the model and the training data can obtain.

6. The combined geological complexity and data density uncertainty data has been plotted as histograms and spatial uncertainty plots showing the variation in uncertainty distribution by increasing the maximum uncertainty value and the borehole radius of influence.

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 [22], for the most probable prediction (the most probable realization/ Best Guess) and tested.

The various geological interfaces bounding the various rock types are handled as Gaussian random fields to which a model of spatial variability describing possible fluctuations around the best guess is applied. Several structural constraints, such as the shape of folds and thickness of layers and stratigraphic relations are accounted for in the model. According to the observations and geological constraints, a variability model is built; the local variance is estimated by application of the simple kriging technique. Finally, the variability is converted into probabilities of occurrence of the various rock masses present in the study area. The probabilities are calculated according to intersection rules governing the stratigraphic sequence of the subsurface model. They enable one to probabilistically model subsurface structures in the form of a three-dimensional (3-D) probability field [22]. It can be useful for identifying areas of greater uncertainties, which can be targeted for further data collection, thus optimizing the site characterization. However the model of uncertainties is centred on the best-guessed geological model, which is arbitrary in essence. The methodology does not attempt to provide an estimation of global uncertainties, which account for wrong choices or omissions made when building up the model. In areas where structures are expected to be complex, the model of variability can be adapted in order to describe such uncertainties.

The TNO–Netherlands Geological Survey GeoTOP model [21], uses stochastic techniques during model construction to compute the probability for each grid cell to belong to a specific lithostratigraphic unit and lithofacies. These probabilities provide a geostatistically based measure of model uncertainty.

Reference [27] suggest the integration of development practices in 3D geological Modelling systems, and the implementation process for uncertainty evaluation in 3D geological structure models, for improving 3D Modelling techniques. The objective of research into uncertainty in 3D geological structure models is to establish a complete theoretical and methodological system for precision assessment and error correction and to generate a complete standard flow frame of precision assessment, error detection and dynamic correction for 3D geological models.

General framework system and main research issues of uncertainty in 3D geological structure models consist of,

1. The methodology for quantification of uncertainty includes spatial statistics and error analysis, theoretical research and empirical analyses such as Classical Error Theory; Regional Variation Theory; Probability Theory; Fuzzy Mathematics Theory; Evidence Mathematics Theory, and Gray System Theory.
2. 3D spatial distribution model of uncertainty in geological structures needs to be formulated using Computer simulation method; method of visualization in scientific computing; superposition and propagation law of uncertainty.
3. Error correction method for 3D geological consist of original data-based error correction method consisting of converting “soft data” (such as subjective interpretation, experience and extrapolation of geologists) to “hard data” which have the strong constraint during the procedure of mathematical interpolation/extrapolation in geological surface verification supplemented with cross-sections and/or virtual boreholes error correction. Interim model based error correction method- remove errors from intermediate geological models directly using true 3D interactive analysis techniques.

VII. Conclusions

Various software environments are available for Modelling, corresponding methodological workflows and their combinations for 3-D geological Modelling can be performed based on the availability of data and the objective of the modelling. The methodological modifications, develop to overcome the shortcomings have added the value and new dimension to the 3-D geological Modelling. The comparison of different Modelling approaches by using the identical set of data indicates differences in the representation or simulation of 3D geology, depending on the specific structural situation of the modelled area. Therefore, the strengths and weaknesses of adequate 3D Modelling software tools and their related concepts need to develop further.In addition,the model validity and associated uncertainties of 3-D Modelling needs to quantify in an easy and clear way readily agreeable to the end users.

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