3D reconstruction of subsurface geological bodies: methods and applications

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Abstract

An original approach for the 3D visualisation and modeling of buried deep and shallow subsurface geological bodies by means of GOCAD is presented in this paper. Cartographic data and structural surface observations have been used, establishing a link between the Geographic Information Systems, where the data are stored, and the GOCAD environment.

Four main sources of information are needed for the development of a 3D structural model:

1 - topographic data represented by contour lines and quoted points;

2 - geological, geomorphological and tectonic boundaries consisting of 2D linear elements;

3 - mesoscopic structural measurements including attitude of planar and linear elements (bedding, thrusts, strike-slip, normal faults, lineations, etc.);

4 - geological cross-section reconstructed through the analysis of surface geological data;

Other sources of geological information as wells data, seismic sections, etc, can be also introduced into the model.

The analysed geological bodies consist of a deep landslide developed in the sedimentary cover of the Southern Alps (Lombardia, Northern Italy), and of the sedimentary successions of the Sant'Arcangelo basin, a recent piggy-back basin located in the Southern Apennines (Basilicata, Southern Italy).

The geometric features of the reconstructed geological bodies can be used to design preliminary monitoring plans or subsurface investigations through seismic surveys and drilling. The characterisation of the shallow subsurface is important for civil engineering and environmental applications that depend upon precise definitions of the geometrical, geomechanical and hydrological properties of rock bodies.

1. Introduction

This paper describes a complete framework for the 3D representation and modeling of deep and shallow subsurface geological bodies. Three dimensional reconstruction is developed in the GOCAD® environment, basing on digital information stored in Geographic Information Systems (GIS) and related databases. These procedures intend to visualise geological information and to establish topological relationships among the analysed objects, coupling the data processing capabilities of GIS (ArcINFO®, ArcView®) with 3D modeling in GOCAD. A simple link among different software is established through a set of conversion programs that make the information, stored in a GIS and related database management system, available on demand.

The proposed procedures have been tested on different geological problems exploiting the same types of data, consisting of geological and structural surface observations directly surveyed in the field. Two examples of 3D reconstruction are here shortly presented. Details on the two case studies are described in other works. The first one concerns the Corno Zuccone landslide, a deep seated slope gravitational deformation developed in a complex tectonic setting within the sedimentary cover of the Southern Alps (Lombardia, Northern Italy) (Crosta et al., 1999, Zanchi & Stelluti, 2000; Zanchi et al., 2001). The second example intends to represent the regional tectonic setting of the Sant'Arcangelo basin, a Pliocene-Quaternary piggy-back structure developed in the internal part of the Southern Apennines (Basilicata, Southern Italy) (Hyppolyte et al., 1994, Roure et al., 1988, Lentini, 1991, Lentini et al., 1994, Lentini et al., 1996). The 3D reconstruction is based on the geological data stored in the CARG Project database realised by the Italian National Geological Survey (SGN) in collaboration with the Italian National Research Council (CNR) (Ardizzone & Sterlacchini, 2000, 2001). Data concern the Sant'Arcangelo 1:50,000 geological sheet (survey Director: Prof. F. Lentini, University of Catania, Italy).

Topographic, geologic, geomorphologic and structural data directly surveyed in the field have been used for this kind of 3D reconstruction in order to generate surfaces which represent stratigraphic and tectonic boundaries(De Kemp, 1999, 2000). The combination of these surfaces leads to the definition of discrete volumes. Regular or irregular grids are obtained by these surfaces where discrete properties can be introduced. Further on, these objects can be used for modeling the spatial distribution of properties, e.g. for slope stability problems, hydro-geological flux models in fractured and porous media, etc.

The use of GOCAD is related to the inadequacy of traditional CAD tools used in geo-modeling. In fact, in spite of their success in modeling simple surfaces, traditional automatic mapping systems are presently unable to model complex surfaces and complex geological objects (volumes) such as thrusts, reverse faults, fold, overturned folds etc.

2. Database structure

The creation of the physical structure of the database has received particular attention for the above mentioned purposes. This step has been realised in ArcINFO®, a powerful GIS very suitable for the storage, management and analysis of vector and raster spatial data. The structure of the database is based on a logical model in which two main categories are detectable:

1 – objects characterised by geometric and descriptive properties (for example, geologic and tectonic boundaries, landslide scarps, counter-scarps, etc.);

2 - objects exclusively characterised by descriptive properties (for example, tables characterising geological units, slide type, activity, involved materials and their mechanical properties, etc.).

Both objects are stored in different geo-information layers. Objects of the first category include points, lines, or polygons layers. Objects of the second type are represented by descriptive tables. The relationships between the geometric elements and the descriptive ones are managed by direct connections (key-columns) of type one-to-one and
one-to-many or many-to-one. In the proposed database model, the above mentioned geometric properties include the primitive forms (points, lines and polygons) and the relationships between them (relation of inclusion, of belonging, of adjacency and sharing). The physical structure of the database was built by means of ARC Macro Language® (AML), a programming language used to organise and customise sequences of ARCInfo commands.

The database has been planned in order to include all kinds of information useful for 3D reconstruction:

- topographic data, including 2D contour lines and quoted points;
- superficial geological and tectonic boundaries, consisting of 2D linear elements;
- morphologic 2D linear elements;
- mesoscopic field structural measurements (attitude of bedding, thrusts, strike-slip, normal faults and gravitational failure surfaces, lineations, etc.) represented as points with properties (strike, dip, dip direction, plunge of lineations, etc.);
- geological cross-sections, reconstructed through the analysis of surface and/or subsurface geological data;
- wells data, mainly consisting of geological descriptions;
- 2D seismic profiles.

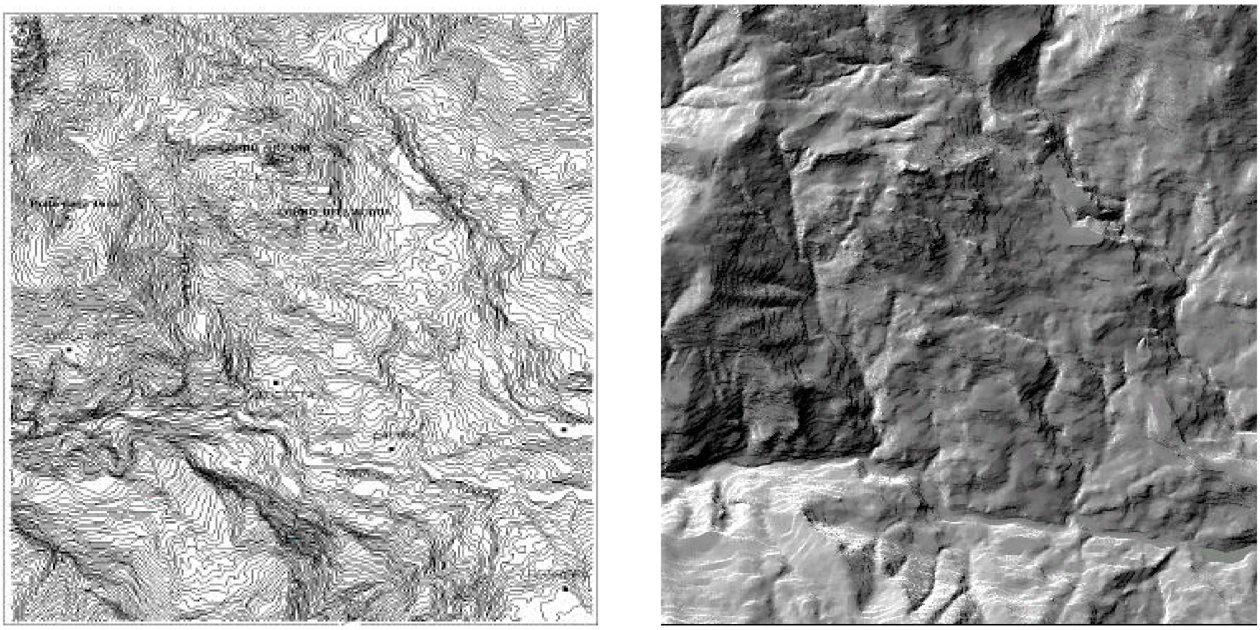

Fig.1 – Topographic map and shaded relief map obtained from the Digital Elevation Model of the Corno Zuccone DSSGD.

3. Topographic data management and analysis with GIS

Pre-3D modeling in GOCAD is needed within the GIS environment in order to prepare a dataset suitable for the purpose of this work. The first problem for vector/raster data management and analysis concerns the quality (scale and detail) of the available topographic maps. In fact, the best compromise must be found between resolution and accuracy. In the first case study, topographic data related to the deep seated slope gravitational deformations (DSSGD) of the Corno Zuccone area (about 16 km^2), the only topographic maps covering the entire study area consist of a 1:10,000 scale technical maps of the Regione Lombardia with 10 m contour lines (fig. 1). By a trial and error procedure, a pixel size of 2.5 m has been adopted. This pixel size correctly describes and represents all the geologic, tectonic and morphologic data, especially trenches, scarps (up-hill and down-hill facing scarps) characterised by a relatively small relief. On the contrary, tests performed on available data using a lower resolution (5-10m) have shown that most of the DSSGD-related features with small amplitude, even if with considerable length, have been masked.

Considering the Sant'Arcangelo case study, covering an area of about 600 km^2, the only available topographic data consist of the 1:25,000 maps of Italian Geographic Military

Institute (IGM). In this case, given the extension of the investigated area, a pixel size of 10 m has been chosen.

Under these assumptions, digital elevation models (DEM) have been derived from a vector to raster conversion of geo-referenced contour lines and quoted points. This operation is followed by a linear interpolation procedure between the pixels with altitude values in order to obtain the elevations of the undefined values in between the rasterized contour lines. This interpolation method in done iteratively and it's based on the Borgefors distance method. Simple operations on the DEM can provide a set of specific maps which can help to define the accuracy of the field surveyed data. Morphometric maps derived from the DEM (such as aspect, slope and longitudinal and transversal concavity/convexity maps) can be very useful for identifying morphological and structural features. In the Corno Zuccone area, for example, it has been possible to study and characterise the dip direction of the planes of movement and to subdivide the slope in different sectors, characterised by quite different behaviors (bulging, deposition, ablation and depletion, etc.). Shaded relief maps and "3D" grids derived from DEM after draping on it raster information (aerophotos, satellite imagery or thematic maps) are sometimes very effective. In fact, they show important details such as the correct location of the main geologic and morphologic elements, allowing for a better understanding of the general geologic setting of the study areas.

4. 3D modeling with GOCAD

Although 3D representations are commonly performed within GIS using DEM, the GIS capability is generally restricted to representation techniques and simulation of simple 3D geometrical features which are often described as 2.5D representations. In fact, the elevation value is considered as an attribute and it's not included within the geometrical description of each element. The recent introduction of 3D elements as polylines-Z in several GIS-oriented software is a first step toward more suitable 3D analyses.

The use of GOCAD leads to a completely different strategy (fig. 2), involving the discrete modeling of natural objects. More specifically, it is based on the following assumptions:

- the geometry of any object can be defined by a finite set of nodes (points) in the 3D space;
- the topology can be modelled by links among these nodes;
- the physical properties can be modelled as values attached to these nodes.

Such a discrete approach is possible by means of a powerful mathematical tool, the Discrete Smooth Interpolator (DSI) proposed by Mallet (1989, 1997), able to interpolate both the physical properties and the location (x, y, z) of each node defining the geological objects in the 3D space. The DSI has been especially designed for modeling natural and complex sub-surface geological structures, taking into account a wide range of data as well as their complexity and variability.

Following this discrete approach, all the data related to geometry, topology and properties of the geological objects stored in the GIS can be retrieved and used for 3D representation purposes. Three basic GOCAD objects have been created with data exported from GIS: a 3D point set (VSet) with elevation values, a line set (PLine) including all the 2D linear elements with no elevation value, and a set of 3D lines representing the down-dip projection of bedding, fault planes, and eventually fold axes. Further information derived from geological cross-sections, wells, and seismic profiles is directly added in GOCAD.

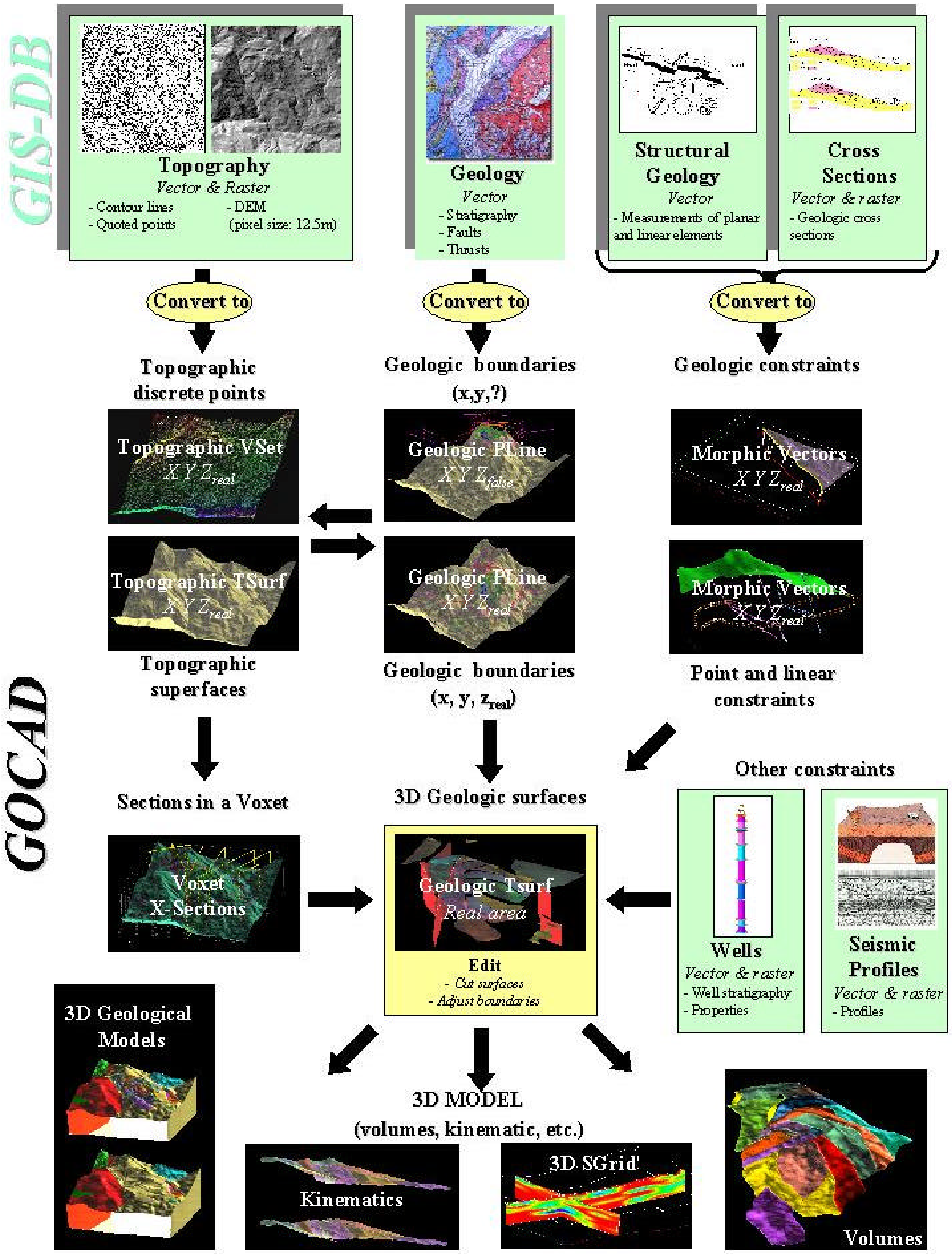

Fig.2 – Flow chart for the 3D visualisation and modeling of geological bodies.

The need of an interconnection between the 3D modeling software and database management systems is evidently a fundamental priority when dealing with large amounts of data as cartographic data which are generally stored in the GIS. In the specific case of GOCAD, the internal objects are not yet directly managed by a database system. A direct access from GOCAD to the GIS database and vice-versa is not yet possible. For this reason, a complete transfer procedure has been developed, basing on selective extraction of data and translation in the GOCAD specific format.

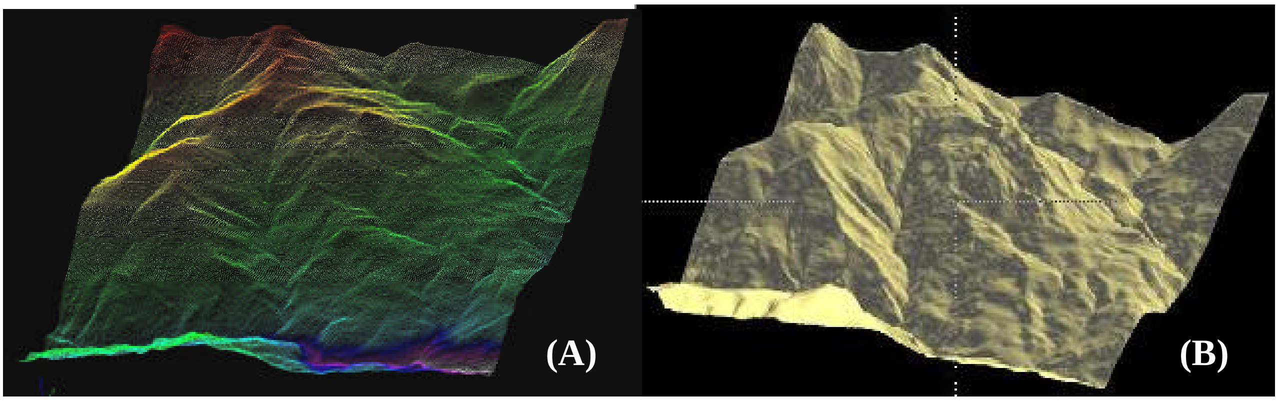

Fig. 3 – 3D topographic reconstruction of the Corno Zuccone area: (A) point data set obtained by means of a conversion procedure from Digital Elevation Model. Visualisation in GOCAD in rainbow colours; (B) topographic surface obtained in GOCAD after interpolation of the point set.

The first step in 3D modeling consists in the construction of the topographic surface (fig. 3). This surface will be used further on to transform 2D linear elements into 3D Plines and to visualise the 3D surface geology. This surface also represents the upper boundary of the volumetric model. Topographic data have been extracted from the GIS-generated DEMs according to the described procedures as a set of discrete points with spatial reference (X, Y) and elevation (Z). Interpolation of these points in GOCAD by means of the DSI takes to the 3D topographic surface.

A different procedure has been used to achieve geologic and geomorphologic linear elements. Lines have been directly imported by means of a conversion program (written in the Avenue® programming language), which directly transforms linear and polygonal elements (*shape* files of ArcView) into the needed format. Each linear elements maintains its specific geometric and descriptive properties defined in the GIS.

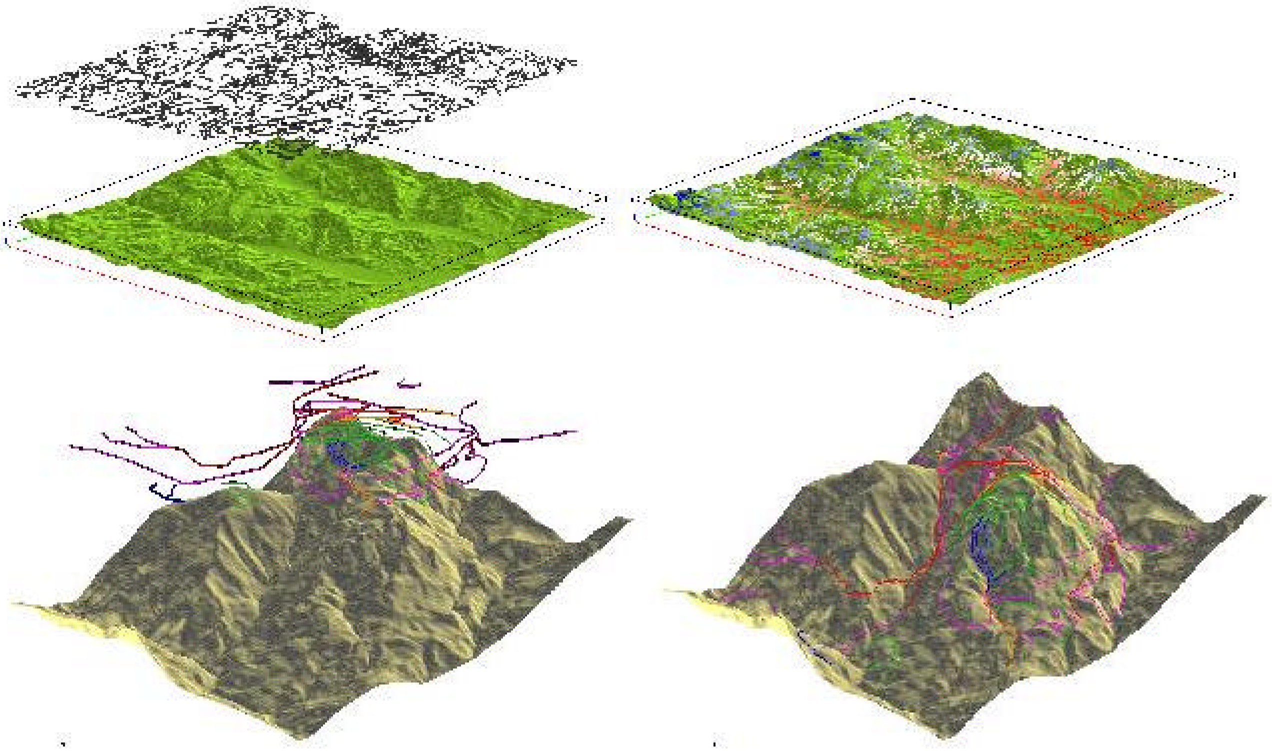

Fig. 4 – Geological boundaries before and after their projection on the topographic surface. The Sant'Arcangelo basin area and the Corno Zuccone area are represented in (A) e (B) respectively.

As GIS generally work with 2D data format, the construction of a 3D geological model requires the attribution of the elevation value to each vertex of the 2D linear elements. From the 3D topographic surface, the elevation value is transferred to the 2D lines which are easily transformed into 3D lines by means of a simple GOCAD operation of projection (fig. 4). Moreover, mesoscopic structural measurements are transformed into down-dip plunging lines of proper length, according to their significance, to be used in the construction of structural surfaces as linear constraints (fig. 5).

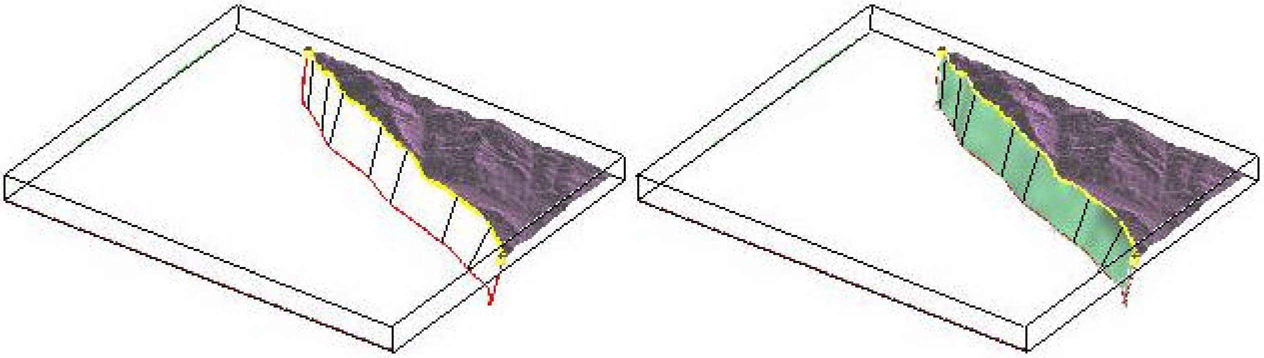

Fig. 5 – 3D reconstruction of the Corleto-Perticara-Scorciabuoi system in the Sant'Arcangelo basin using down-dip plunging lines, obtained from surface geometry of the structure as linear constraints.

Starting from the 3D topographic surface, a 3D regular grid (Voxet) is built. Here geological cross-sections (X-Sections) are traced following the geological complexity of the study area and available information (fig. 6). Some of the 2D sections were previously balanced in order to check the 2D geometrical consistency of the model.

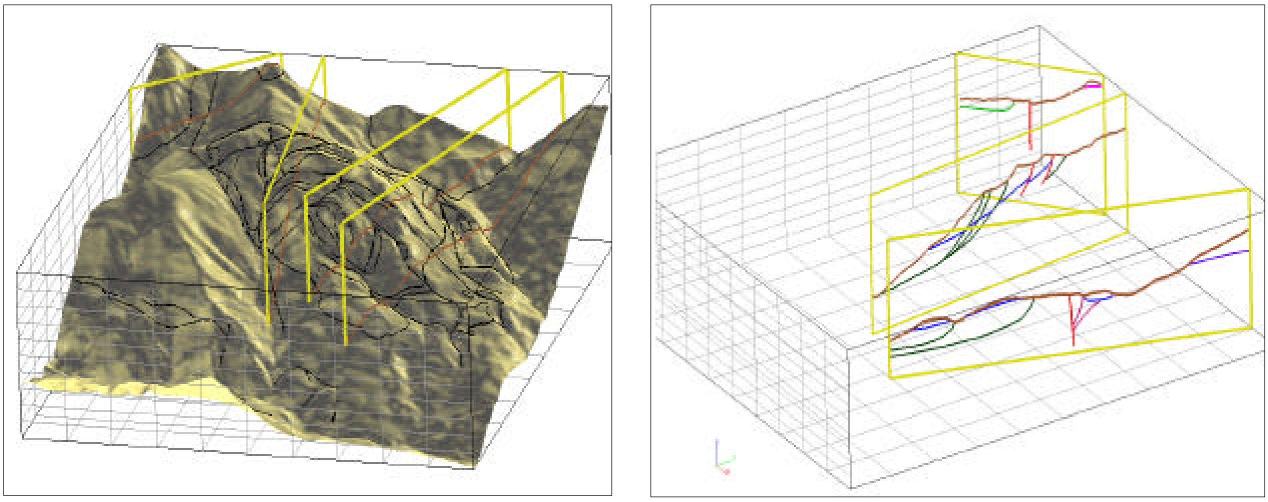

Fig. 6 – 3D regular grid (Voxet) in which geological cross-sections are traced.

The further step concerns the construction of the buried planar elements (fig. 7) such as stratigraphic and tectonic surfaces (e.g.: thrust, strike-slip faults, etc.), and, in the case of the Corno Zuccone landslide, the slip planes due to sliding. Superficial cross-cutting relationships among the different structural elements must be firstly established, in order to model their subsurface relationships.

Each single surface is then obtained through the interpolation of the following linear elements: the superficial trace of the structures, the linear elements derived from mesoscopic observations (morphic vectors), and the linear elements derived from the 2-D sections. All these elements are considered as constraints which must be honoured during the generation of the model. After generating single surfaces, intersections are detected and computed, basing on previous constraints. In this way a 3D topology is established.

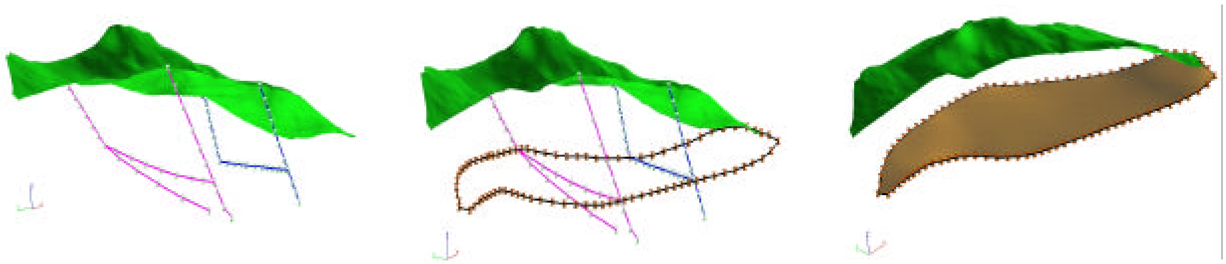

Fig. 7 – Example of 3D reconstruction of a buried geological surface in the Corno Zuccone study area by means of linear elements as constraints.

4.1 Description of the geological case studies

The first case study deals with a deep landslide occurring in the Lombardian Prealps, the Corno Zuccone (CZ) sackung, firstly described by Crosta et al. (1999) as a deep seated slope gravitational deformation (Varnes et al., 1989) The slide is developed within a small carbonate mass, the CZ klippe, and consists of the Norian Dolomia Principale Fm. which overthrusts the so-called Taleggio Unit. The lower unit here includes shales and marls of the Argillite di Riva di Solto Fm. Gravitational slip planes displace both the carbonate upper mass and its plastic tectonic substratum, suggesting a recent down slope movement of about 100-150 m. Strike-slip fault systems separate the CZ klippe from the Corno del Bruco klippe, which consists of Ladinian carbonates of the Calcare di Esino Fm.

Fig. 8 – The three main strike slip fault systems and the basal thrust surfaces of the Corno Zuccone klippe are here represented.

In this specific case, we have distinguished three main fault systems (fig. 8): two south-dipping thrust systems bounding the Corno Zuccone and Corno del Bruco klippen, two major strike-slip faults, and ENE-WSW gravitational slip surfaces. Cross-cutting relationships suggest that the fracture systems associated with the formation of the landslide are the youngest structures in the area. Strike-slip faults clearly post-date thrust motion of the Corno Zuccone and Corno del Brucco klippen which are thus the earliest structures. Moreover gravitational structures sharply end at the two strike-slip fault systems, which mark the lateral NW and NE boundaries of the slide, thus working as lateral constraints of the gravitational deformation. According to this scheme, the reconstruction of the surfaces began from the gravitational structures, then passing to the strike-slip and thrust faults. Combining the obtained planar elements, closed 3D surfaces have been built, representing, e.g., the klippe of Corno Zuccone and the slided rock mass. The Sant'Arcangelo area shows a complex structural setting, achieved during the recent evolution of the Apenninic fold and thrust-belt. The area is characterised by an embricate hinterland-dipping thrust stack including several tectonic units which over-thrust the Apulian units at a depth of about 4 km. The western part of the study area is dominated by the NNW-SSE striking Armento Line, an east-vergent thrust which stacks Late Paleogene and Miocene turbiditic units upon the Pliocene marine deposits of the Caliandro Group. This unit is tectonically covered by Mesozoic carbonates and Miocene Flysch deposits. The central part of the Sant'Arcangelo 1:50,000 geological sheet consists of the Pliocene-Quaternary succession of the Sant'Arcangelo Group related to the formation of a piggy back basin unconformably covering the older sediments of the Caliandro Group.

Three main units have been distinguished basing on lithofacies definition. ESE-WNW open folds and NW-SE normal faults occur in this area. The Sant'Arcangelo basin is bounded to the north by the ENE-WSW striking Corleto-Perticara-Scorciabuoi left-lateral transtensional fault system. In the north-eastern part of the geological sheet the fault system branches out forming a positive flower structure which crosses older N-S trending folds and thrust systems. Cross-cutting relationships suggest that the fault is very recent in time.

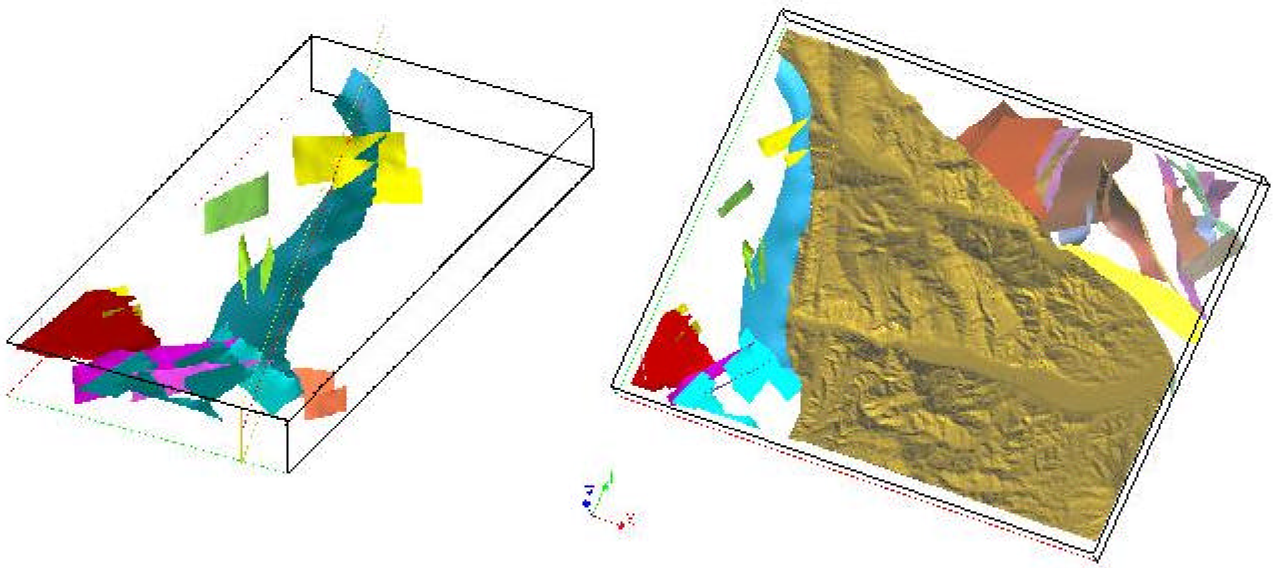

Fig. 9 – Example of 3D reconstruction of buried geological surfaces in the Sant'Arcangelo basin area. In particular, on the left, the ramp and flat geometry of the Armento line, located in the westernmost part of the study area, is represented.

The 3D reconstruction performed in this case study was based on the surface geology, focusing on the main tectonic structures, which have been previously described. Structural analysis suggests a ramp and flat geometry for the central part of the Armento line, passing to a steep lateral ramp in the westernmost part of the area (fig. 9). The Corleto-Perticara-Scorciabuoi transtensional system has been reconstructed using down-dip plunging lines deduced from its superficial geometrical character (fig. 5).

Finally the central part of the basin, including the Sant'Arcangelo Group was reconstructed using a dense grid of cross-sections. Three main stratigraphic units have been distinguished. From east to west they mainly consist of conglomerate, sandstone, and marly clay. As the three formations are etheropic, some simplification has been introduced in order to represent the transitional character of the lithological boundaries.

5. 3D applications

The obtained 3D reconstructions can be used for several applications (fig. 10).

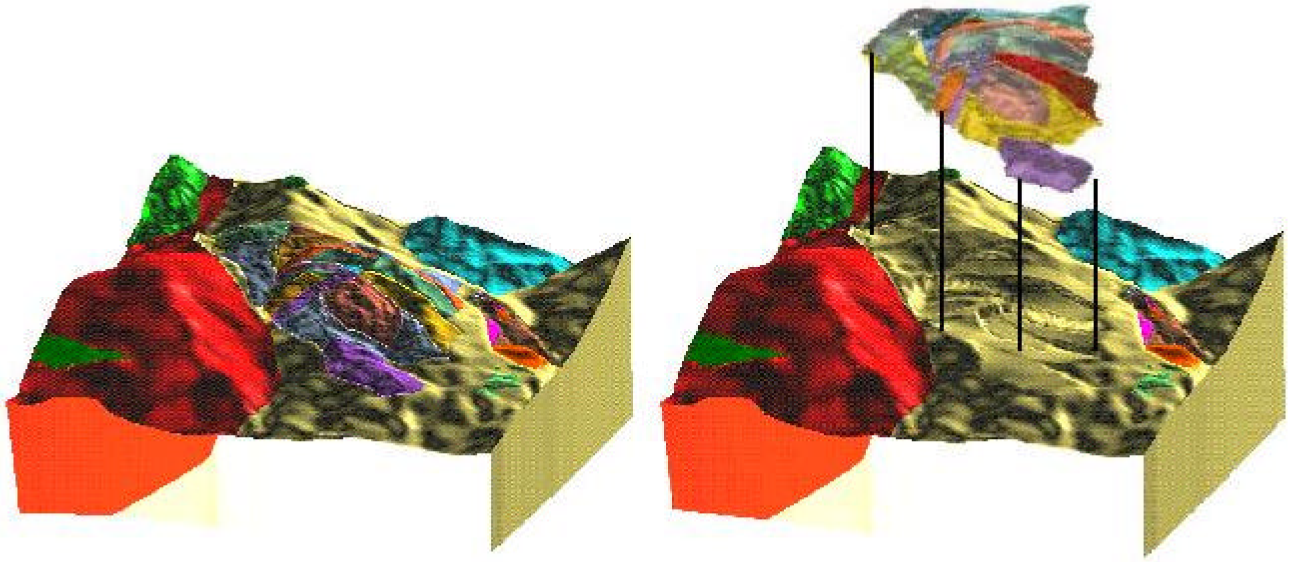

Fig.10 – 3D geological model of the Corno Zuccone DSSGD. Light brown is the Argillite di Riva di Solto of the Taleggio Unit; the different blocks forming the CZ klippe (Dolomia Principale Fm.) are represented in various colours; red on the left is Calcare di Zu Fm.; light blue, in the back, is Calcare di Esino Fm., forming the Bruco klippe; green in top left is a small klippe of Dolomia Principale Fm.

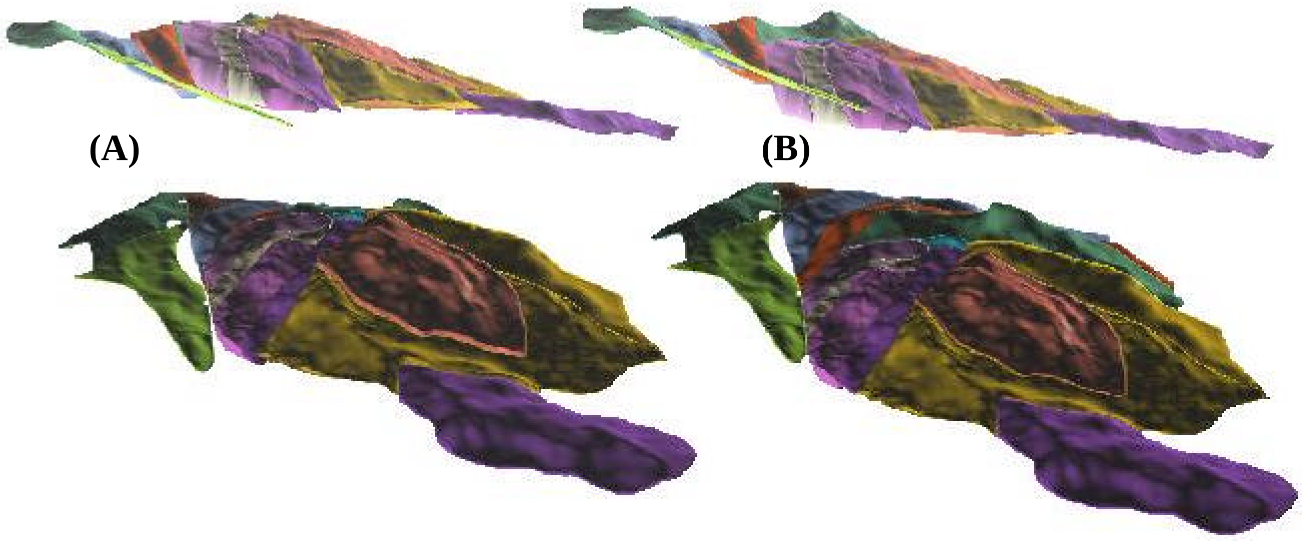

Fig. 11 – Kinematic modeling of the Corno Zuccone klippe. (A) Pre-sliding situation; (B) Post sliding situation.

For example, in the specific case of the Corno Zuccone landslide, kinematic modeling can be performed. According to the geometry of the reconstructed faults and gravitational structures, each block can be restored to its pre-failure position in order to check the consistency of the reconstructed displacements and the initial geometric features (fig. 11).

A comparison between the results of this 3D reconstruction and previous 2D balancing has generally confirmed our basic assumptions: dip-slip motion along gravitational features, limited block rotation along listric faults (5°-10°), evaluation of displacements, and reactivation of the lateral strike-slip faults as oblique-slip faults during the formation of the sackung.

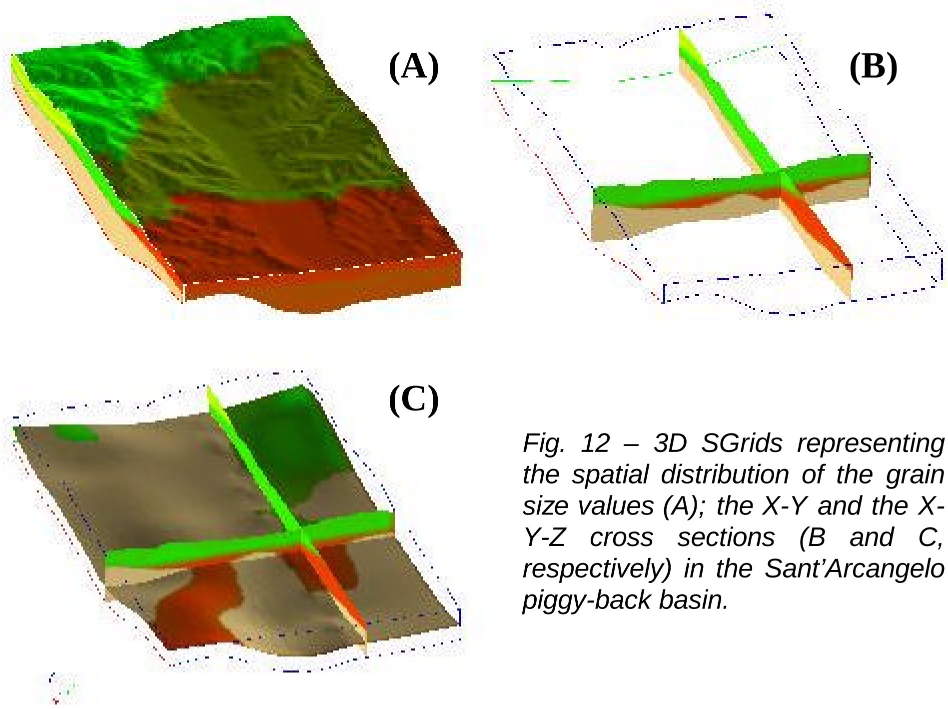

Fig. 12 – 3D SGrids representing the spatial distribution of the grain size values (A); the X-Y and the X-Y-Z cross sections (B and C, respectively) in the Sant'Arcangelo piggy-back basin.

Moreover, the geometric features of the reconstructed geological bodies can be used to design preliminary monitoring plans or subsurface investigations in the most favourable areas. 3D grids, obtained from the geometrical model, could be used for slope stability modeling by means of finite or distinct elements codes.

In the case of the Sant'Arcangelo basin, applications concern the construction of a 3D parametric grid for the sedimentary successions deposited within the piggy-back basin. Basing on the set of surfaces obtained interpolating linear elements from surface geology and cross-sections, a stratigraphic grid was generated to represent granulometric parameters (fig. 12). The upper boundary of the grid is represented by the surface topography, the lower one by the unconformity occurring at the base of the Sant'Arcangelo Group. The sedimentary body representing the Sant'Arcangelo Group has been internally divided into three lithological units according to the aforementioned criteria. Due to the transitional character of the boundary between these units, the granulometric distribution has been modeled simulating a progressive variation of the grain size across the lithological boundaries. Relating hydrogeological parameters (porosity, permeability, transmissivity, etc.) to the obtained volumetric model, groundwater potential resources may be assessed by means of the 3D distribution of the permeable layers.

6. Conclusion

The procedures described in this paper enhance the possibility of using 2D GIS-related information, usually contained in geological maps, as input data for 3D reconstruction of complex geological bodies. 3D models have been obtained through several steps, which can be summarised as follows:

- data mining (extraction) of 2- and 3D information from the GIS;
- pre-processing in order to obtain the required peculiar data format needed for 3D modeling in the GOCAD environment;
- construction of the 3D model in GOCAD using superficial structural data, subsurface interpretations, such as cross-sections, etc.
- other data obtained from different sources of information, as wells, seismic sections, etc., can be eventually used as direct constraints to check the accuracy of the model.

Although the construction of such models has a large rate of uncertainty, due to the real lack of subsurface information, a 3D visualisation of "a possible geometrical solution" gives a great help to the understanding of the structural setting. Moreover geometrical inconsistencies can be generally recognised through the construction of the 3D virtual model taking to several stages of editing and corrections, also when the model is based on detailed field mapping and balanced 2D cross-sections. Moreover, these geometrical inconsistencies have also suggested revisions of the field work, leading to a general improvement of the final reconstruction.

Relatively quick and cheap modeling using available data can help to constrain in situ investigations, minimising times and direct costs.

On the other hand, unsolved problems are related to:

- the definition of standard procedures relative to field data collection for 3D analysis;
- the possibility of establishing a direct link between available database management system and GOCAD.
- interface with specific program (FLAC, UDEC, etc.) for numerical modeling.

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