

3D geo-mapping based on surface data for preliminary study of underground works: A case study in Val Topina (Central Italy)

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ABSTRACT

This paper reports a geological modelling procedure suitable for the reconstruction of three-dimensional models and for applications in preliminary tunnelling studies. The geological modelling is based on field survey data stored and organized in a database using a Geographic Information System (GIS) and then exported in a Computer Aided Design (CAD) software system, which is used to create the geometrical model. The main steps of the elaboration are: 1. reconstruction of the Digital Terrain Model; 2. calculation of elevation for the 2D geological data; 3. reconstruction of geological cross-sections oriented perpendicular to the geo-structural (fold) axis (geological profiles) by means of down-plunge projection; 4. modelling of the geological surfaces via NURBS interpolation. A model built in this way can be used to automatically create sub-horizontal geological cross-sections at tunnel level or vertical cross-sections along the alignments in order to define accurately the geo-lithological characteristics along each underground segment during excavation and to calculate the segments lengths in every geological formation along the tunnel.

The authors delineate the procedure through a simple, and yet exhaustive, case study carried out in order to choose the optimal path for the Foligno–Nocera Umbra railway (mainly in tunnel) to be realised in Val Topina (Umbria Region, Italy).

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1. Introduction

Subsurface geological and structural analysis has undergone a considerable evolution due to the use of three-dimensional reconstruction techniques: the traditional methods for geological reconstruction can be speeded up and rendered more accurate by using computer and find be useful in various engineering geological themes (Tirén et al., 1999; Pinto et al., 2002).

In this paper the authors describe a methodology for creating and validating three-dimensional geological models based on surface geo-structural data stored and organized in a database managed by a Geographic Information System (GIS). The geological data can be handled by a Computer Aided Design (CAD) in order to create geological surfaces using the Non-Uniform Rational B-Splines (NURBS) geometry. Starting from a 3D model, geological cross-sections with different orientations can be automatically created, in order to describe the geometry of the geological structure along the underground segments of the alignments. This is then used to provide accurate geological information for shrewd technical and financial preliminary design (Vähäaho, 1998; Elkadi and Huisman, 2002; Hack et al., 2006).

This approach is described using a case study, part of an agreement drawn up between “CGT – Centro di GeoTecnologie” of the University of Siena and Italferr S.p.A. (client and designing company), about a geological study of the Rocaccia-Acqua Bianca area (Foligno, Umbria Region, Italy) for a preliminary project of a new railway segment.

Designers initially proposed two possible alignments characterised as follows (Fig. 1):

- Alignment 1: 4221 m long, including two underground segments of 2598 m total length, and two above ground segments of total length of 1493 m;
- Alignment 2: 4213 m long, including only one underground segment of 3851 m total length, and two above ground segments of total length of 362 m.

The aim of this work is to perform the detailed reconstruction of subsurface geological structures' geometry only using surface geological data collected in the fieldwork. Once the 3D model had been completed, it had been combined with the results of both geomechanic rock mass characterisation and environmental impact assessment (which are not discussed in this paper) in order to choose the better solution for alignment in terms of technical and financial reasons.

2. Geological outline

Aside from the acquisition of literature map data, as would be usual, this geological study started by building stereomodels through digital

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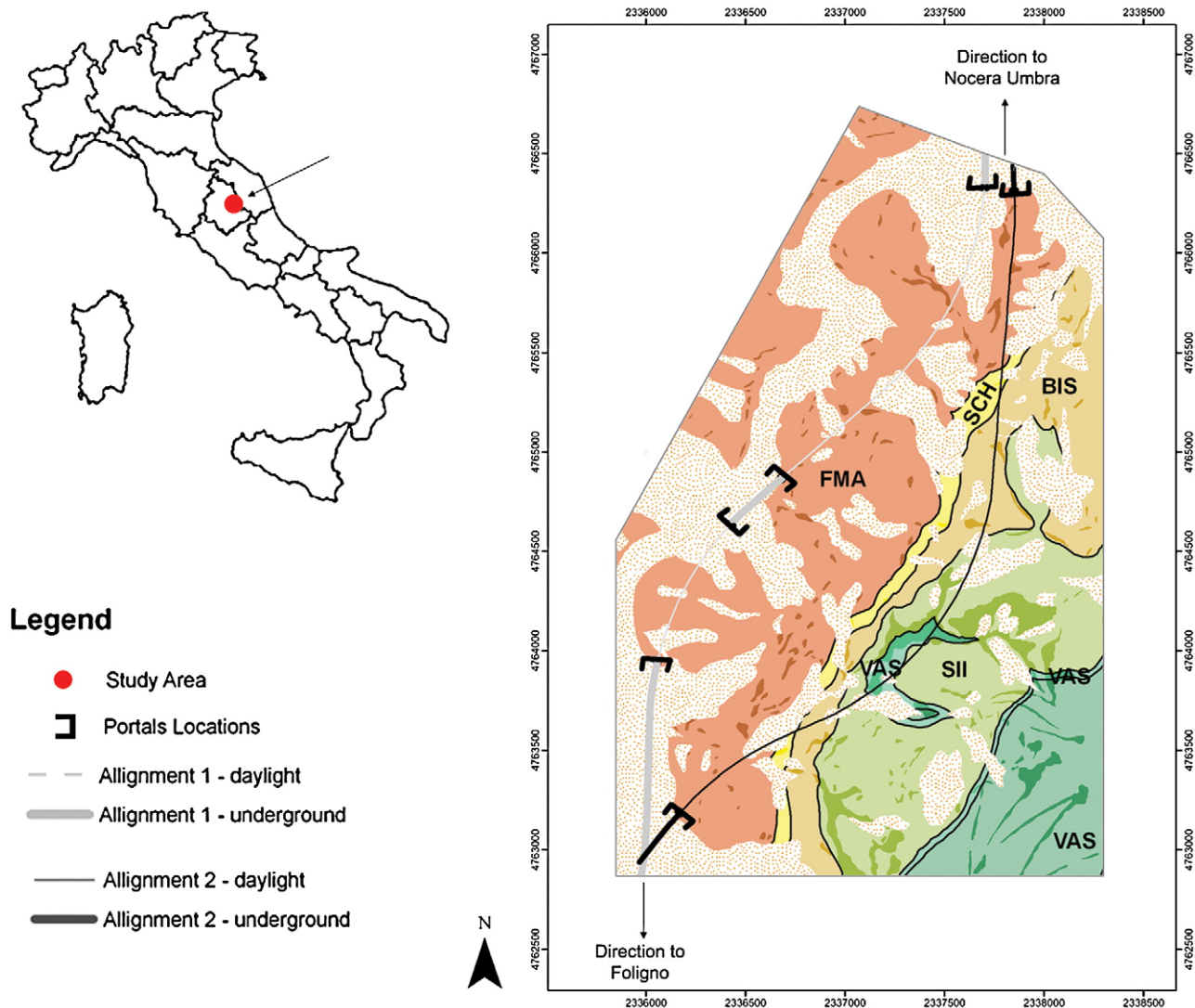


Fig. 1. Study area and localisation of two new alignments proposed by designers. The geological map in the right shows quaternary deposits (orange dotted area), bedrock (light colours) and outcrops (darker colours). The geological formations are the following: SGO – “Scaglia Rossa”; VAS – “Scaglia Variegata”; SII – “Scaglia Cinerea”; BIS – “Bisciaro”; SCH – “Schlier”; FMA – “Marnoso Arenacea”.

photogrammetry techniques, using detailed panchromatic aerial photographs. The analysis of stereomodels was for both key beds recognition and outcrops mapping. This was then useful for the subsequent traditional geo-structural survey on field, on a scale of 1:5000.

The study area is located in the “Umbro-Marchigiano” Italian northern Apennines. The Neogene–Quaternary evolution of this part of the mountain belt shows a progressive north-eastward migration of orogenic deformation. The rocks of the “Umbro-Marchigiana” sequence (Upper Triassic–Pliocene; [Accordi and Morelli, 1968](#); [Moretti and Perno, 1968](#)) are deformed by folds with NW–SE oriented axes. Such structures are the surface effects of fault-propagation folding below ([Calamita et al., 1990](#)).

On a small scale, anticlines generally have an asymmetric box shape, with a plate top and either vertical or overturned eastern flanks. Their axial surface plunges towards south-west, giving the sense of a general tectonic transport toward north-east. Particularly, in the study area limestone–marlstone rocks of the upper part of “Umbro-Marchigiana” Sequence outcrop.

The structural pattern of the surveyed area, moving from west to east, is represented by two first order structures, kilometric North–South syncline and anticline, with a westward fold axial plain and in the core have sandstones and calcarenites of “Marnoso-Arenacea” Formation (outcropping in the whole Topina Valley), and calcareous

marlstones of “Scaglia Rossa” Formation (the structure of “M. Mezzo – Il Monte” mountains) respectively ([Barchi, 2002](#)). The fold axis plain does not crop out in the study area.

These structures link up in the west to the “M. Mezzo – Il Monte” mountains, where the sheared normal flank is deformed by gravitative

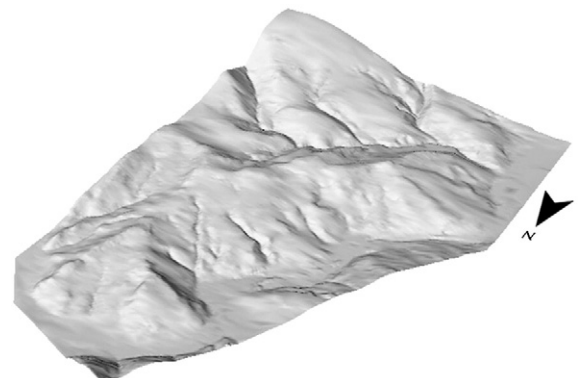


Fig. 2. Digital Terrain Model of the study area reconstructed using a NURBS surface and seen from North–West.

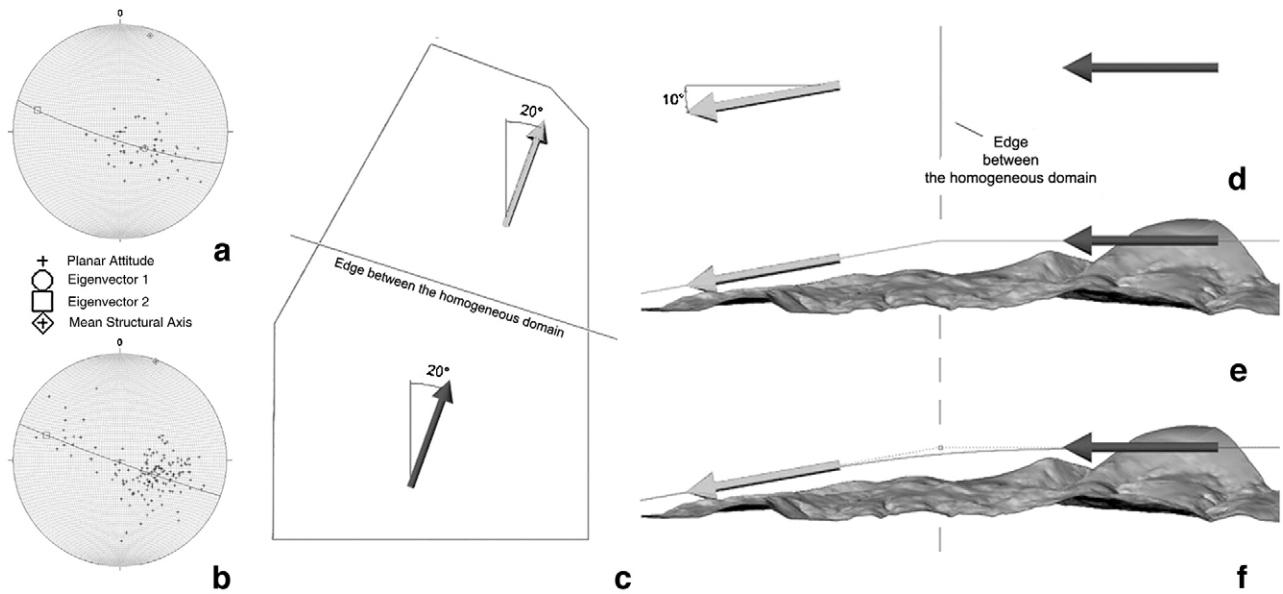


Fig. 3. 3D graphical representation of the mean fold axis in the study area: (a) stereo graphical attitudes projections (lower hemisphere) of the northern homogeneous domain and (b) the southern homogeneous domain. (c) Representation of the axis using arrows in vertical visualization and (d) lateral visualization from left. (e) Reconstruction of the mean fold axis using two polylines and (f) using a unique NURBS curve with Grade equal to three.

collapse asymmetric minor folds, with small angle (0° – 10°) axial plain, eastward plunging (N 20°). Such folds locally yield the overturning of stratigraphic sequence.

The outcropping rocks of the study area belong to the following five Formations of the “Umbro-Marchigiana” Sequence, listed as follows starting from the oldest one:

1. “Scaglia Rossa”: rosy limestones and calcareous marlstones, well stratified, with layers and nodule of red flint. The inferred total thickness is 300 m (lower Turonian p.p.–Lutetian p.p.). “Scaglia Variegata”: succession of polychrome limestones, marly limestones and clay marlstones; it represents the transition between “Scaglia Rossa” and “Scaglia Cinerea” Formations. The thickness is approximately 30 m (Lutetian p.p.–Priabonian p.p.).
2. “Scaglia Cinerea”: greyish and reddish fissile calcareous marlstones and clay marlstones. The passing from “Scaglia Variegata” and “Scaglia Cinerea” Formations is by a progressive increase of fine fraction to marl-calcareous’ detriment. The imputable thickness is 110 m (Priabonian p.p.–Aquitania p.p.).
3. “Bisciaro”: light grey limestones and marl limestones, with frequent layers of black flint, and local insertions of greyish clays. This geological formation has both greater calcareous content and lower clay content than the higher “Schlier” Formation and the lower “Scaglia Cinerea” Formation, respectively. So, “Bisciaro” Formation has more competence and gives more energy to the morphology. Its thickness is 55 m (Aquitania p.p.–upper Burdigalian p.p.).
4. “Schlier”: succession of greyish marlstones, clay marlstones, calcareous marlstones, generally with less clear stratification. In the study area outcrops of this formation are very scarce because, generally, eluvium deposits cover the rocks. The inferred thickness is approximately 40 m (middle and lower Miocene).
5. “Marnoso Arenacea”: succession of turbiditic sandstones and marlstones levels. The thickness of the sandstone layers varies from a few centimetres (near the passing to the “Schlier” Formation) to 60–70 cm (in the western part). The thickness of the whole formation is not assessable, as the upper part of the formation does not outcrop, however the minimum thickness is probably 700 m (Accordi and Morelli, 1968; Moretti and Perno, 1968). Sandstones, coarse light brown massive, are prevalently composed of quartz and

feldspar, whilst thinner layers are composed of silt, grey marlstone and calcareous marlstones, often banded. The sand/clay ratio is between 1/5 and 1/10. Frequent calcareous turbiditic insertions (calcareenites 1–2 m thick, with marlstones insertions) are laterally continuous (called “columbine”), so they can be considered as a key bed (middle and lower Miocene).

During the fieldwork the outcropping areas were defined from the areas without exposed rock due to quaternary cover or vegetation. In the outcropping areas it is possible to observe the rocks and take measurements; in the non-outcropping areas the geological data have to be inferred. This kind of classification provides indications on the reliability of the position of geological data on the map.

3. Initial data preparation using GIS

The data collected in the field were stored in a geographic data base (GDB) edited in ESRI® ArcGIS™ 9 (Michael et al., 2000) and structured

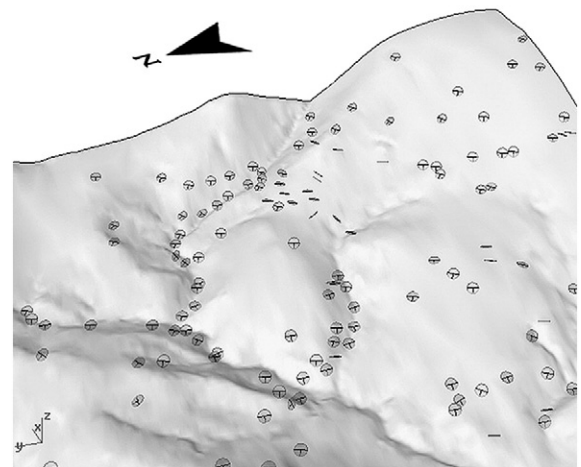


Fig. 4. Visualization of the 3D symbols that reproduce the attitudes orientation.

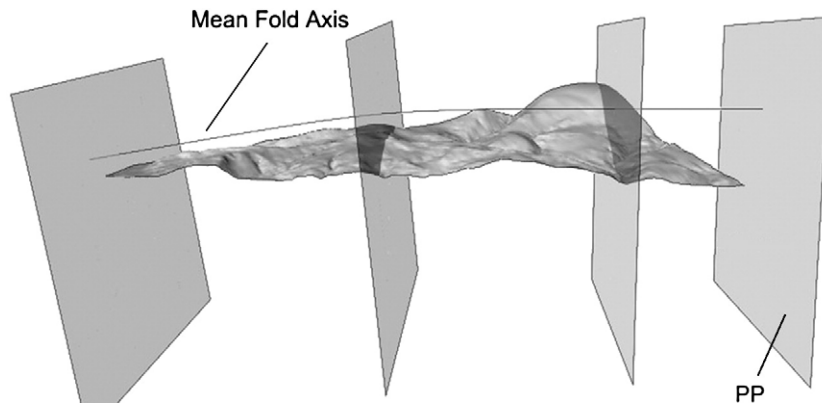


Fig. 5. Some examples of Projection Planes.

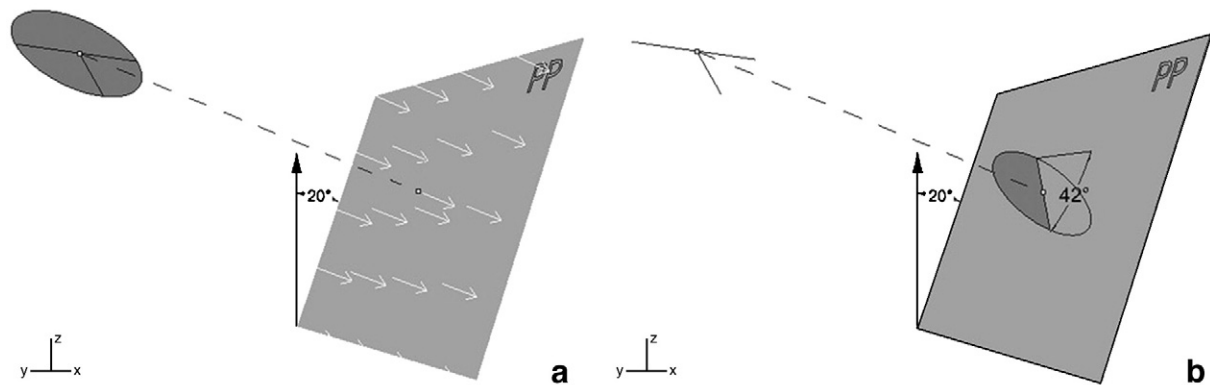


Fig. 6. Example of an attitude projection on a PP (attitude dip: 50° , angle between the attitude azimuth and plane attitude: 60°): (a) the first step is the down-plunge projection of the attitude localization (with point) on the PP; the down-plunge direction is defined by the white arrows (perpendicular to the PP). (b) Reconstruction of the apparent dip angle by intersection between the attitude plane and the PP (the apparent dip in this example is measured on the PP).

according to the guidelines for the elaboration of the geological database of the Italian Geological Survey ("CARG-CARTografia Geologica" project, see [Artoli et al., 1997](#)). The geological data were stored in the GDB on the basis of their geometrical shapes: points (attitudes of bedding), lines (observed geological boundaries, limits of outcropping areas) and polygons (outcropping areas, geological units) with additional alphanumeric data description (i.e. azimuth and dip attitude orientations) stored in the related tables.

The data were digitalized on screen according to a topological scheme arc/node ([Bonham-Carter, 1994](#)) in the national Gauss-Boaga reference system, using ERSI ArcMap™. In this first part, only point and linear data were digitalized. The integration of the data base with the polygon geometries and the geological boundaries in the covered areas will be discussed later.

The topographic map on a scale of 1:5000 in DXF (Drawing Exportable Format) of the study area was inserted into the GDB; these data included elevation (Z) and were therefore suitable for creating the DTM. The geometry of the two alignments was directly furnished by the Italferr Company in vector format endowed with the elevation. These data were inserted in the GDB in the same way as the numerical topography had been.

4. 3D geometrical reconstruction of the geological model

The 3D geological model was built using the CAD software Rhinoceros® 3.0 (hereafter referred to as Rhino). It allows to model curves, surfaces and volumes using the NURBS geometry ([Robert McNeel & Associates, 2003](#)). The NURBS surfaces can be imagined as

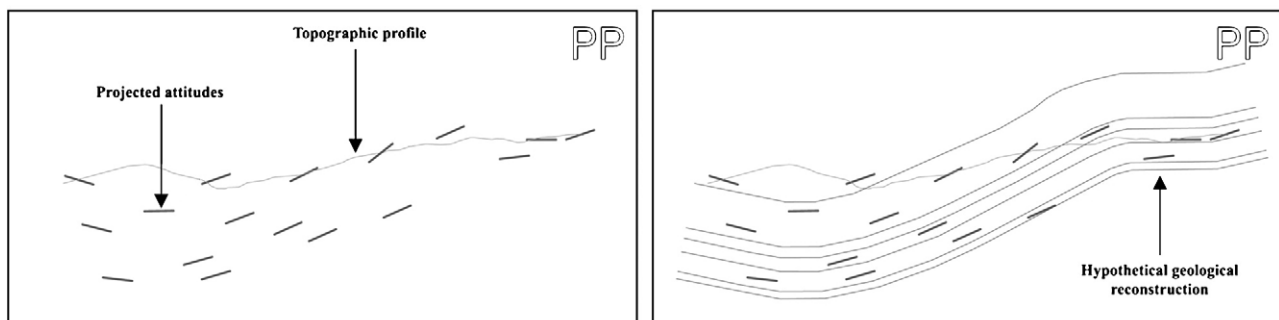


Fig. 7. Prospective view of a PP and example of geological profile reconstruction starting from the geological data projected on the PP.

elastic and deformable surfaces which use a base structure to take form. This structure is composed of a network of curves directed according to two principal directions which are perpendicular to each other. The shape of the curves, and therefore of the surfaces, is defined by four fundamental characteristics: Control Points, Curve Degree, Knots and Evaluation Rule (Piegl and Wayne, 1995 for detailed information). The NURBS interpolation is suitable for geological modelling because it is able to create smooth and congenial surfaces, which provide realistic representations of geological contact surfaces, in this and other cases (Fisher and Wales, 1990; De Kemp and Sprague, 2003; Sprague and De Kemp, 2005).

4.1. DTM creation using NURBS

The geometries digitalized in the GIS environment are 2D without Z-elevation expressed; the digital terrain model can be used to assign elevation values to the geological data in order to make them 3D.

The contour lines of the topographic map contained in the GBD were extrapolated and used to create the DTM via Natural Neighbour interpolation (Maune, 2001) in ESRI® ArcMAP™. The relief was reproduced through a topographic grid with a cell size of 2.5 m (half of the contour lines vertical distance used in order to avoid loss of accuracy, Moore et al., 1993). From this raster an ASCII XYZ point file was generated, where the X and Y coordinates describe the point at the centre of each cell in the grid, and Z is the mean elevation of the cell. These points were imported into the CAD environment Rhino and used as Control Points of a NURBS surface that reproduced the terrain of the study area (Fig. 2).

4.2. 3D reconstruction of the geo-structural axis

Starting from a geo-structural statistic analysis (Ramsay, 1967; Davis, 1973 and references therein) of the attitudes collected in the study area (Fig. 3a and b) it was possible to identify two homogeneous geo-structural domains: one with a mean fold axis orientation of 20° of azimuth and 0° of dip in the southern area, and the other with a mean fold axis orientation of 20° of azimuth and 10° of dip in the northern area. These orientations can be represented in a 3D space with arrows localized in the middle part of each homogeneous domain as described in Fig. 3c and d. The design tools available in Rhino allow for a reconstruction of a continuous axis through two lines that meet each other on the “edge between the homogeneous domains” (Fig. 3e). These lines can be substituted by a unique NURBS curve with Curve Degree higher than 1 and with one Control Point localized at the limit where the homogeneous domains meet (Fig. 3f): the NURBS geometry provides a smooth and realistic variation of the geo-structural axis between the homogeneous domains.

4.3. Geological data: from GIS to CAD

The stratification measurements collected in the field had to be transferred into the CAD environment. In the geological database they are organized as georeferenced points with attributes that describe their angular value of azimuth and dip. A simple exportation from GIS causes the loss of information regarding the attitude orientation. In order to avoid this problem a procedural automation of tasks was created to produce a symbology describing position and orientation of planar attitudes in a 3D CAD as reproduced in Fig. 4. The tasks were automated using a program created in Microsoft® Visual Basic Language™ called Attitude Design (Simoncini and Tonini, 2005; contact the corresponding author for a free copy).

Conversely, the linear geological data can be directly converted in DXF and imported in Rhino as georeferenced polylines. These linear data, as already mentioned above, are two-dimensional objects without any information regarding their elevation. The Z coordinates were added through vertical projection on the DTM NURBS.

4.4. Reconstruction of structural profiles

The geological data imported into the CAD environment were used to create geological profile: geological sections oriented perpendicular to the geo-structural axis. The methodology of geological profiles' creation is based on “classical” techniques usually used in structural geology but supported by automated calculus in order to improve speed of execution and accuracy.

The first step was the creation of planes oriented perpendicularly to the curves that represent the mean fold axis of the study area as represented in Fig. 5. These planes are called projection planes (starting from here referred to as PP, or Down-Plunge Projection; Tonini et al., in press). The geological data can be automatically projected onto a PP. The projection of the punctual position of an attitude expresses its localization on the PP (Schetselaar, 1995); the intersection between the attitudes surface and the PP defines the apparent attitude's dip. The steps described above are represented in Fig. 6.

Using the available standard CAD tools it is possible to obtain the topographic profile (intersection between the DTM and a PP) and reconstruct the geologic profile (Fig. 7) using NURBS curves. The geological profiles must be drawn beyond the topographic profile in order to facilitate the check of the surface and volume reconstruction (described in the following sections).

4.5. Geological surfaces

The geological model can be reconstructed through interpolation of several geological profiles distributed in study area. Only a certain number of profiles are made, taken at various points in the area, which are then used for the creation of model, reducing the construction time. In this case only seven profiles were used: three starting profiles in the southern border, on the edge between the homogeneous domains and in northern border (respectively Profile 1, Profile 5 and Profile 7 in Fig. 8); the other profiles were added with the aim of achieving better description of local geological variations (i.e. local overturned folds).

The interpolation was performed in Rhino using NURBS surfaces (Fig. 9). In order to avoid discrepancies the surfaces were forced on the profiles: the Control Points of the profile curve Control Points were also used as Control Points for the incoming geological surfaces as well. The Degree was manually set to 3 in order to create true space-curves and surfaces.

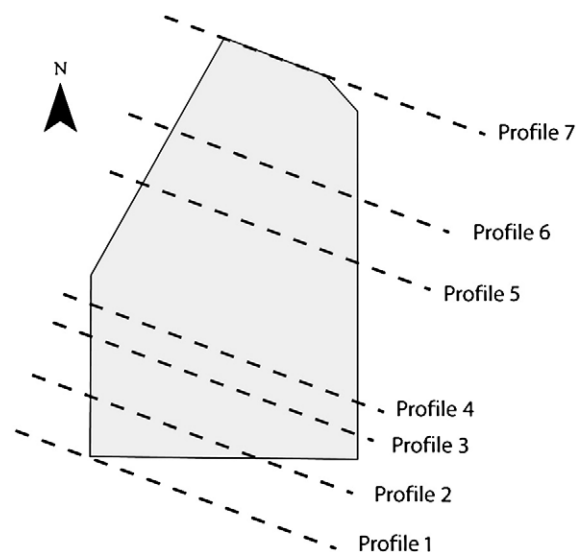


Fig. 8. Localization of the geological profiles built for the creation of 3D geological model.

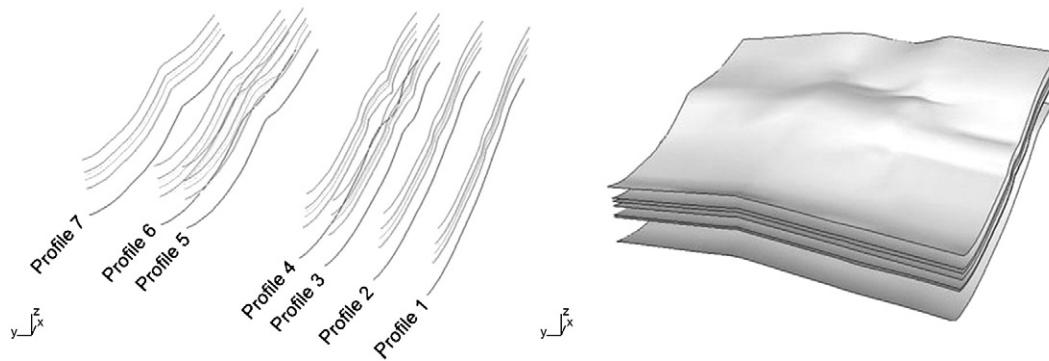


Fig. 9. Reconstruction of the geological surfaces through NURBS interpolation of the geological profiles.

4.6. Methodology to check the surfaces created

Once the surfaces are created, a quality control check is needed. This validation can be made by checking whether the surfaces geometry honours the field data.

As described in Fig. 10a and b, the intersection between the DTM and the geological surface creates the Model Contact Lines (MCL, see Tonini et al., in press), the MCL's can be considered as a “model geological map” (Fig. 10c and d): its comparison with the outcropping geological data can highlight errors in geometry of the modelled surfaces (inferred geological data were not used in order to avoid errors due to subjective geological interpretation).

There are many sources of these errors, but the most common are:

- Erroneous interpretation of the projected data and consequently erroneous reconstruction of the geological profiles. In this case it will be necessary to discover which geological profile caused the error, to perform the corrections and to produce a new interpolation surface.

- Errors due to locally non-perfect cylindrical structure and presence of local geological variations.
- Erroneous strata thickness estimation.

A flawless superimposition between the MCL and the geological data can be obtained through a procedure of trial and error, by analysing the errors, making the corrections and creating new surfaces subject to verification. Verifications on the MCL quality were performed by means of new punctual geological surveys giving feedbacks to improve both the geological map and MCL.

4.7. Volumes representation through B-rep

The representation of the volume of a geological formation clarifies the geological geometry of the formation unlike a 2D geological map, and allows computing the object mass, volume, and weight.

Once the contact surfaces were reconstructed and verified using Rhino, the volume of each geological formation was reconstructed

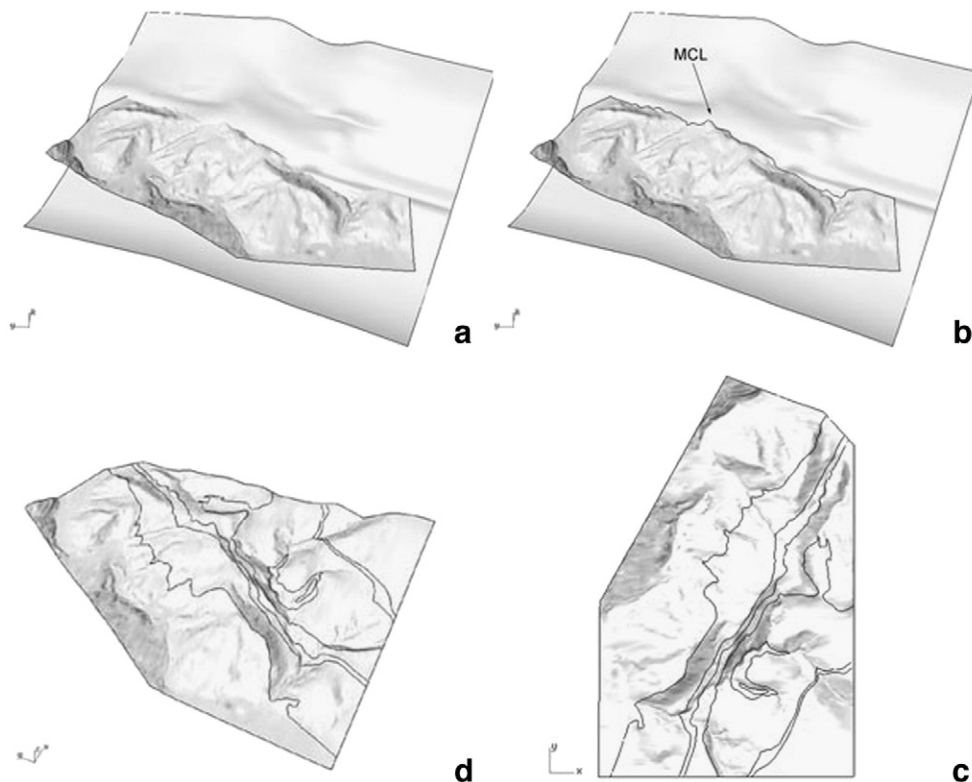


Fig. 10. (a, b) Example of creation of a Model Contact Line through intersection between the DTM and a geological contact surface. (c) Tri-dimensional visualization of the MCLs and the DTM of the study area. (d) Vertical orthometric representation of the Model Contact Lines and the DTM.

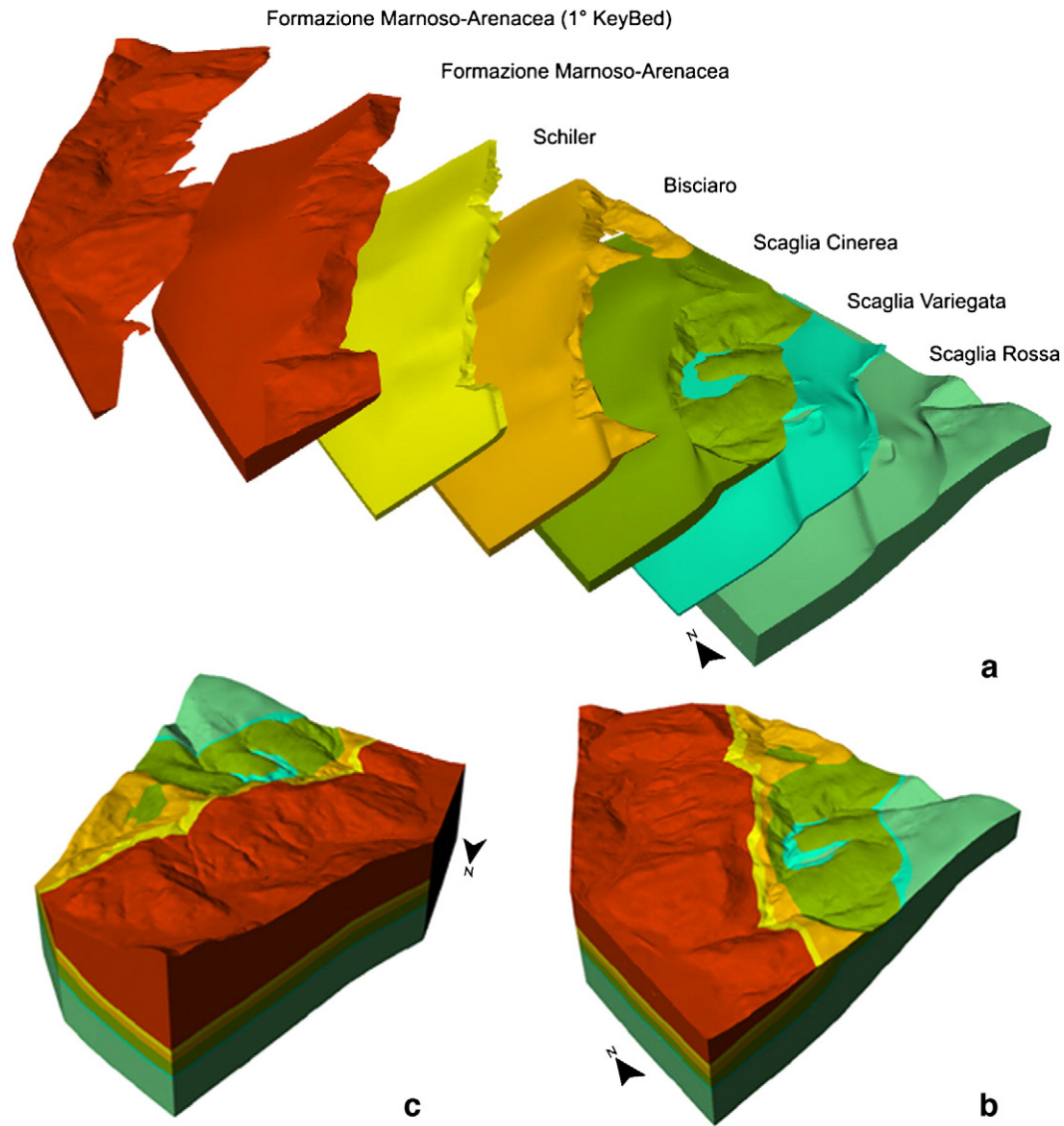


Fig. 11. Representation of the geological model using B-rep: (a) model explosion with indication of every geological formation outcropping in the study area. (b) Visualization of the model from South–West and (c) from North–West.

using a set of closed surfaces, this kind of representation is called B-rep (Boundary Representations, see [Zhong et al., 2006](#)).

This group of closed surfaces, for each geological formation, is composed of: the contact surface with the overlying formation; the contact surface with the underlying formation; the portion of the DTM where the formation crops out; the lateral limits of the model ([Fig. 11](#)).

5. Integration of the geological database

At this moment of the procedure in the GDB are contained only the outcropping geological data; it can be integrated with the boundary lines in the covered areas in order to obtain a printable geological map.

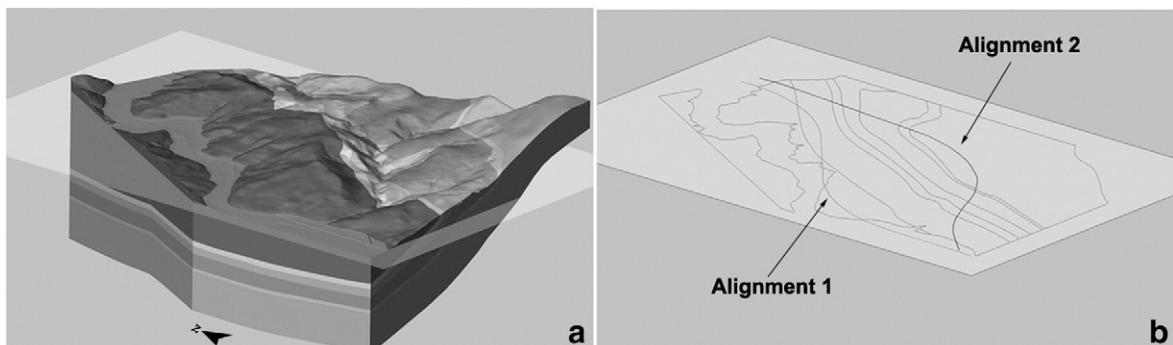


Fig. 12. (a) Representation of the 3D geological model and the plane located at the alignments level. (b) Intersection between the model and the plane: sub-horizontal geological cross-section at the tunnels level.

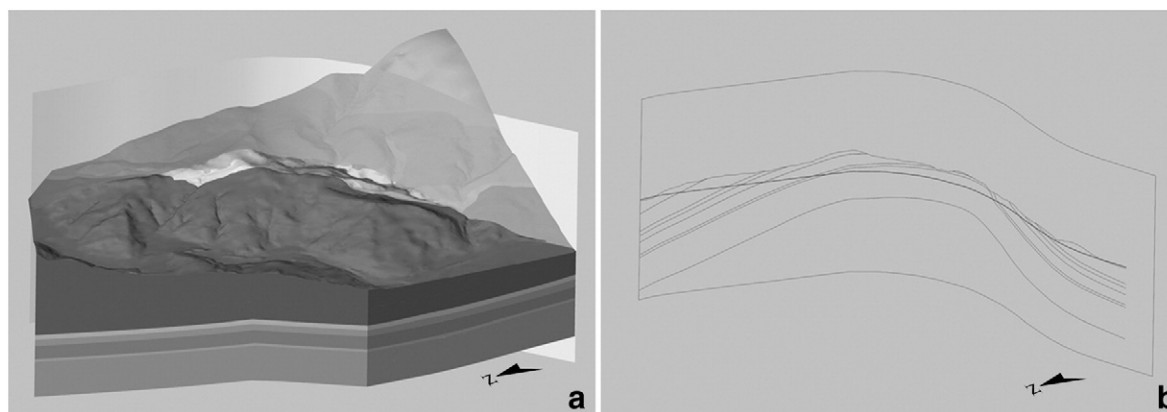


Fig. 13. (a) Representation of the 3D geological model and the section surface obtained by extrusion of the Alignment 2. (b) Non-planar geological cross-section along the Alignment 2.

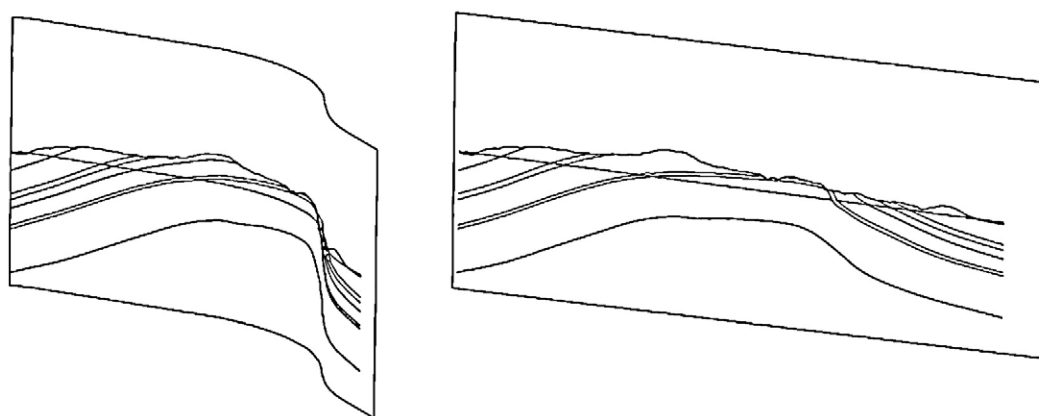


Fig. 14. Vertical cross-section along the Alignment 2 (on the left, see also Fig. 13b) and the same cross-section “unrolled” (on the right).

The MCLs have geographical reference information and they are continuous in covered areas; these factors make them suitable for use as a reference to obtain the geological boundaries in the non outcropping areas. They were calculated in two-dimensions in the CAD environment, then exported as DXF and imported in ESRI® ArcMAP™ 9, where they were cut by means of the other linear occurrence (limits of the outcropping areas). The portions of MCLs located in the covered areas were selected and topologically integrated in the GBD. Starting from the linear geometry strata, the polygonal geometries (outcropping areas and geological units) were automatically created to finally complete the GBD.

An appropriate graphical symbology was recreated in ArcMAP™ and assigned to every geological occurrence contained in GDB in order to obtain a printable layout.

6. Geo-lithological analysis along tunnels

The 3D geological model can be used to describe the geological conditions along the tunnels. So, it is necessary to export the alignments geometry from GIS to CAD using the DXF format: the result is two polylines (NURBS curves with degree equal to one) with Z expression. The alignments are located in the same plane (Azimuth 222°, Dip 0, 83°) that was reconstructed in Rhino (Fig. 12a); the intersection between this plane and the geological model was automatically performed in order to create an explanatory sub-horizontal geological cross-section at the alignments level (Fig. 12b).

The Rhino's tools permit the creation of non-planar sections too, an example are the vertical cross-sections along the alignments: two extrusion planes were created starting from the alignments (Fig. 13a where the Alignment 2 is taken as example) and then used to create

the intersection with the model surfaces (Fig. 13b). This cross-section can be properly seen in a 3D space but is not well represented in a “classical” paper document. This problem was by-passed unrolling the cross-section in Rhino (Fig. 14).

Polylines describing the alignments geometry were cut by means of the model's surfaces in order to define the tunnels segments in every geological formation and automatically calculate their length. The percentages of tunnels length in every geological formation is given in Table 1.

Table 1
Percentages of tunnels lengths in every geological formation

Lithology	Geological formations	Alignment 1 (% of tunnel length)	Alignment 2 (% of tunnel length)
Limestones with decimetric thickness stratification	Scaglia Rossa		37.7%
	Scaglia Variegata		4.5%
	Scaglia Cinerea		14.2%
	Bisciaro Schlier		6.4%
	Formazione Marnoso Arenacea		5.0%
Pelitics and siltitics with small sandstones intercalations	Formazione Marnoso	44.2%	28.1%
	Arenacea		
Pelitics and silts with frequent intercalations of sandstones and calacarenites	Formazione Marnoso	44.2%	4.1%
	Arenacea		
	(1° Key Bed)		

7. Discussion and conclusion

The proposed procedure for three-dimensional geological models of subsoil is based on well-known techniques, such as creating geological cross-sections and utilising NURBS interpolation. However, we would like to point out that this approach was planned and developed to reconstruct subsoil structure using inexpensive collected data, also very useful for subsoil reconstruction: the surface data collected during geological survey. Moreover, this method reduces the subjectivity in rebuilding geological structures, considering already observed data (outcrops), avoiding data deriving from certain interpretation, which so subjective, such as, for instance, presumed stratigraphic contacts in covered areas. Geological profiles, created on the basis of geo-structural data on projection planes (PP), were used to create geological surfaces by means of NURBS interpolation. It is clear that the geoscientist interpretation affects geological subsoil reconstruction, so the re-built geological contact surfaces were checked by Model Contact Lines (MCL), which are the result of intersection among interpolated geological surfaces and Digital Terrain Model. Inconsistency of MCLs with surveyed data shows a geometrical error of geological surface to be corrected by modifying geological profiles more often than acting on parameters of NURBS geometry. Since MCLs respect surface surveyed data, the geological model is correct, so MCLs, considered as geological contacts, continuous in both outcrops and covered zones, constitute the new geological map in GIS environment. This approach could lead to unexpected results, even in cases where the modelling is based on traditional geo-structural techniques made both quicker and more accurate through three-dimensional CAD tools, like Rhino software. The effectiveness of geometric reconstruction of subsoil by NURBS interpolation consists in several aspects such as smoothness, elaborating and editing simplicity, and, last but not least, because it allows to model by both curves (for instance fold axis trace) and surfaces (contact surfaces or faults). Three-dimensional modelling also permitted to create quickly either planar or curve sections and calculate geological formations volumes through which the tunnel passed, besides creating and verifying continuous geological models. Combining these results with cost benefit analysis, rock mass geomechanics and environmental impact studies, the railway designer is able to optimize the selection of the tunnel path.

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