3D geological modeling for slope stability problems. 

The case study of the Corno Zuccone sackung, Val Taleggio (Italy)

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ABSTRACT

A 3D geological reconstruction of the Corno Zuccone sackung, Val Taleggio, Bergamo, was carried out by means of GOCAD, a special software for 3D applications. The sackung occurs in the sedimentary cover of the Southern Alps, within a klippe of Dolomia Principale (DP) thrust upon the plastic shale of the Argillite di Riva di Solto Fm. (ARS). The klippe is bounded by strike-slip faults which constrain the subsequent gravitational movements.

Topographic (contour lines) and geological data (geological, structural, and geomorphological linear elements, cross-sections, faults and beds attitude), previously stored in a GIS, have been translated and imported into GOCAD for the construction of the 3D model. 3D modeling has allowed the internal consistency of the input data to be checked, thus improving the geometrical and kinematic interpretation of the sackung.

A 2D geomechanical model has been built through a discrete elements code, in order to analyse the mechanism of formation of the sackung, based on the obtained 3D reconstruction. 2D and 3D models both suggest the occurrence of a basal sliding surface located within the ARS causing a horizontal shift of about 150 m of the slide rock mass.

KEY WORDS: 3D geological reconstruction, Gocad, sackung, GIS, discrete elements, weak rocks.

INTRODUCTION

3D reconstruction of complex and irregular geological bodies is now possible through the use of special software developed for this kind of problems (Linx, 1997; GOCAD, 1997; Earth Vision, etc.). Although several examples of integration among different data have been published on subsurface structures studied through bore-holes and geophysical investigations, few applications concern the use of traditional cartographic data and mesoscopic structural information.

In this study we apply such techniques, based mainly on the use of surface cartographic information, stored in a Geographic Information System, to the reconstruction of a deep seated slope gravitational deformation (DSSGD) developed within the sedimentary cover of the Southern Alps (Crosta et alii, 1999) in the upper part of the Taleggio Valley, Italy (fig. 1). The DSSGD occurs in a complex structural framework dominated by brittle structures which have been reconstructed with GOCAD. GOCAD is a special 3D-oriented software based on a particular algorithm, the discrete smooth interpolator, developed by Mallet (1989) for 3D modeling.

Geological and structural information based on detailed surveys was firstly integrated within a Geographical Information System and then translated and imported into GOCAD. The 3D model was reconstructed through several steps which will be described in this paper.

Basing on the obtained geometrical reconstruction, a 2D numerical model has been built with a discrete elements code in order to check the mechanism of formation and evolution of the sackung.

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The Taleggio Valley is located within the sedimentary cover of the Southern Alps, here characterised by a complex system of imbricate thrust sheets including Mid-Late Triassic carbonate and terrigenous successions. The lower thrust sheet, here named Taleggio Unit, consists of a thick succession, Norian to Liassic in age. The Argillite di Riva di Solto Fm. (ARS) forms a large part of the study area, covering the thick massive carbonates of the Norian Dolomia Principale (DP) which occurs in the lower part of the Taleggio Valley. The ARS includes a lower member with shales and marls and an upper member consisting of marls, marly limestones, and calcilutites (JADOUR et alii, 1994). West of Vedeseta it is covered by marls and coral limestones of Calcare di Zu, passing upward to the massive oolitic grainstone of Dolomia a Conchodon (fig. 1).

Two thrust sheets are stacked above the Taleggio Unit, the Corno Zuccone and Corno del Bruco klippen, consisting of strongly fractured carbonate masses which gently dip southward (ZANCHI et alii, 1989; SCHONBORN, 1992; JADOUR et alii, 1994). The Corno Zuccone (CZ) klippe entirely consists of DP, including massive dolostones and dolomitic breccias. Breccias crop out west of the Valle del Chignolo forming a thin thrust sheet strongly dismembered by vertical faults and superficial slides. A small thrust sheet, consisting of gypsum and cataclastic dolostones (San Giovanni Bianco Fm.), occurs west of the Valle del Chignolo below the western part of the CZ klippe. The Corno del Bruco includes the Ladinian recifal limestones of Calcare di Esino.

The CZ klippe is sharply bounded by strike-slip faults: the Valle del Chignolo N-S system on the left, and the Valle dell’Acqua NW-SE system to the right of the klippe. Along the Valle del Chignolo we mainly observed evidence of left-lateral motion followed by minor normal dip-slip and dextral oblique reactivations, whereas the NW-SE fault separating the CZ klippe from the Corno del Bruco unit suggests dextral motion, post-dating thrust
stacking. Small E-W and ENE-WSW normal faults are also evident in the upper part of the klippe. The lower part of the area is covered by Pleistocene fluvial deposits of the Reggetto and Olda units (fig. 1). They suggest the occurrence of an important paleo-drainage system, antecedent to the excavation of the Taleggio gorge. The position of these deposits indicates a strong erosion and dissection of the relief.

MORPHOLOGICAL FEATURES

The massif of CZ displays impressive morphological features due to gravitational sliding such as large downhill facing scarps, up-hill facing scarps and trenches related to the DSSGD (fig. 2). Most of the main features are exposed within the CZ klippe, which shows E-W to ESE-WNW striking south-dipping sliding planes (fig. 1). These point out a general S/SSW down-slope extension of the entire structure. Three main parallel and continuous scarps, striking ESE-WNW, can be recognised across the sackung, from the Valle del Chignolo to Reggetto. Their occurrence in this area, where the upper member of the ARS outcrops, suggests that the DSSGD strongly affects also the upper part of the Taleggio Unit lying below the carbonate klippe.

A vertical throw of about 100 m of the southern portion of the klippe is suggested by the main scarp, which bounds the summit of CZ. Despite their continuity, the main scarps have been successively crossed by transversal NNE-SSW trending fractures, splitting the sackung into several portions with different behaviour. As a consequence, the NW part of CZ moved toward the Valle del Chignolo, and the SW portion toward Regetto.
ties can be assigned. Furthermore, closed surfaces can be moved, cut, and glued. The combination of surfaces leads to the construction of discrete regions, to which properties can be assigned. Moreover, cut-and-fill simulations allow a better understanding of the general pattern.

On the other hand, any element used in GOCAD has a 3D orientation software is a first step toward more suitable 3D analyses.

Fig. 4 - Flow chart for 3D modeling with GOCAD starting from data stored in a GIS and related database. – Diagramma di flusso relativo alla modellazione 3D con GOCAD partendo da dati archiviati in un Sistema Informativo Territoriale e nel relativo database.

The lower part of the CZ slope consists of marls and shales of the ARS and is affected by important landslides, especially around Vedeseta and Lavina. NW-SE trending trenches and long rectilinear scarps, just south of Vedeseta, point out the presence of deep sliding surfaces, possibly joining the main one close to the Enna River. Continuous movements have damaged the main roads and the bridge on the Enna River. Moreover, the southward diversion of the Enna River along the entire width of the CZ sackung can be related to the progressive movement of the whole slope.

DATABASE MANAGEMENT: FROM GIS TO 3D MODELING

Although 3D representation is commonly carried out within Geographic Information Systems (GIS), through the elaboration of digital elevation models (DEM), GIS capability is generally restricted to representation techniques and simulation of simple 3D geometrical features. In fact, the elevation value is considered as an attribute and it is not included within data topology. The recent introduction of 3D elements as polylines-Z in several GIS-oriented software is a first step toward more suitable 3D analyses.

Morphometric maps derived from the DEM (e.g.: aspect, slope, longitudinal and transversal concavity/convexity maps) can be useful to recognize morphostructural features, associated to a possible dip direction of the planes of movement, and for subdividing the slope in areas with different behaviours (bulging, deposition, ablation and depletion, etc.). Shaded relief (fig. 3) and 3D grids resulting from the DEM, after draping it with raster information (aerophotos, satellite imagery or thematic maps), can be effective in the description of huge slope movements, showing the main morphologic elements and allowing a better understanding of the general pattern. On the other hand, any element used in GOCAD has a 3D topology and any kind of object such as points, lines, surfaces, grids, solids can be easily represented, edited, moved, cut, and glued. The combination of surfaces leads to the construction of discrete regions, to which properties can be assigned. Furthermore, closed surfaces can be used also for the creation of regular or irregular grids where discrete properties can be introduced.

We will focus on the first steps in the definition of a 3D model, such as the creation of the main surfaces which define the basic structure of a geological body, and on its use for the reconstruction of a complex slide. This procedure can be adopted for the reconstruction of any kind of geological body, assuming that geometrical characters and cinematic evolution are known.

For this purpose, a computerised record-keeping system was created in order to carry out a variety of operations on topographic, geologic and geomorphologic data related to the case-study. Besides the normal database operations, its structure has been thought to provide information available on demand for specific application programs (GOCAD, UDEC). The database structure is based on a logical model in which two main categories are defined:

- objects characterised by geometric and descriptive properties (e.g.: scarps, counter-scarps, geologic and tectonic boundaries, etc.);
- objects characterised by descriptive properties (e.g.: tables indicating the slide type, activity, involved materials and their mechanical properties, etc.).

In the proposed database model, geometric properties include both the primitive forms (points, lines and polygons) and the relationships among them. In this way mapping information can be stored, analysed, easily retrieved and eventually translated and imported into GOCAD.

Three main categories of information have been used for the development of a 3D structural model (fig. 4):

1) topographic data (contour lines);
2) 2D geological linear elements corresponding to stratigraphic, tectonic and morphostructural boundaries;
3) mesoscopic measurements including attitude of bedding, faults and sliding surfaces.

As GIS generally work with 2D data formats, the first problem for the construction of a 3D model consists in the attribution of the elevation value to each vertex and node of linear elements. This operation has required the construction of a DEM using the 1:10,000 scale map of Regione Lombardia. The DEM has been derived from a vector to raster conversion of georeferenced 10 m contour lines, followed by an interpolation procedure. A pixel size of 2.5 m has been adopted to correctly describe and represent morphological elements as scarps and trenches characterised by a relatively small relief. A set of points has been extracted from the DEM along a regular grid and imported into GOCAD for the reconstruction of the topographic surface.

Structural measurements have been transformed into down-dip plunging lines of appropriate length (50-100 m for each measurement according to their significance) to be used in the construction of structural surfaces as linear constraints.

PROCEDURES FOR 3D MODELING WITH GOCAD

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 geological
Fig. 5 - 3D modeling with GOCAD. A: importing linear elements with a fixed elevation value (2,500 m) from GIS into GOCAD above a topographic surface reconstructed with a point set obtained from a DEM. B: projection of linear elements upon the topographic surface. C: location of X-sections in a voxel (3D regular grid). D: Construction of complex geological bodies through the generation of surfaces obtained from linear elements. E: definition of the CZ sackung into 3 main bodies. After removing each body, the basal slip surface is visible in the last picture.

linear elements with no elevation value and a set of lines (morphic vectors) representing the down-dip attitude of bedding and structural planes. The geological model has been constructed in GOCAD using this data set, and adding further information from cross-sections (fig. 4).

The first step concerns the reconstruction of the topographic surface through the interpolation of the point set extracted from the DEM obtained from GIS. From this surface, properties such as elevation are transferred to the 2D geological boundaries, which are easily transformed into 3D lines (figs. 5a and 5b). Once that the elevation value has been attributed to these linear elements, the topographic surface can be cut into several 3D polygons in order to reproduce, for example, a 3D representation of the surface geology.

Starting from the 3D topographic surface, a 3D regular grid (voxel) is constructed where several geological cross-sections (x-sections) have been traced according to the geological complexity of the area and available information (fig. 5c). The further step consists of the reconstruction of the buried surfaces including slip planes due to gravitational motion, and tectonic surfaces (e.g.: thrust, strike-slip faults). In order to reconstruct the fault grid affecting the CZ klippe, cross-cut relationships among the different tectonic structures must be firstly established. According to field observations, gravitational surfaces are the most recent ones and can be divided into two different sets: ENE-WSW fracture systems related to the formation of the sackung and recent scarps related to activation of minor slides. Strike-slip faults clearly post-date thrust motion of the CZ and Corno del Brucco klippen which are 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 sackung, working as lateral constraints of the gravitational deformation. We began the reconstruction of fault grids from the gravitational structures, successively constructing strike-slip and thrust faults. Each single surface has been
obtained by means of interpolation of the following linear elements: the superficial trace of the structures, morphic vectors, and linear elements derived from the 2-D sections (fig. 5d). Due to their superficial trace and mechanical properties of the displaced rock bodies, gravitational structures are supposed to be listric, progressively flattening within the tectonic substratum of the carbonate klippe consisting of the plastic ARS shales. The reconstructed planes have been supposed to join a basal <detachment> surface. This has been reconstructed by connecting the main scarp with the traces of the two strike-slip faults bounding the sackung and with the traces of the drainage pattern, as suggested by superficial evidence. Once the general fault-grid has been reconstructed, the main geological bodies are obtained joining parts of the reconstructed surfaces. In this way closed 3D surfaces are constructed (fig. 5d). Applications to the reconstruction of the main bodies of the sackung are presented in fig. 5e.

One of the most complex structural problems concerns the reconstruction of the thrust surface stacking the CZ klippe above the Taleggio Unit. In fact, the thrust surface crops out only along the eastern margin of the klippe and has been displaced by the most recent faults and especially by gravitational structures. The thrust dips to S/SE, becoming flat in the southern sector around Regetto, where small isolated klippen occur. Further information on the geometry of this surface has been obtained from the basal thrust in the westernmost sector of the klippe, west of the N-S vertical strike-slip fault of the Valle del Chignolo. Here the thrust surface is very shallow and almost parallel to the topographic surface. Optimisation of the geometry of the thrust planes, through the check of their lateral consistency, superficial displacement and mapped superficial boundaries, led to the final construction of the structural model after several stages of editing and corrections (fig. 6). Geometrical inconsistencies detected through the construction of the virtual model suggested some revision to the field work, taking to the correction of imprecision and field mapping mistakes. The reconstructed bodies consider the basic constraints imposed by the geological observations, as the displacement along the main scarp of the sackung, surface geology and mesoscopic data.

The obtained reconstruction of the CZ klippe can be used in terms of cinematic analysis. According to the geometry of the reconstructed faults and gravitational structures, each block can be easily restored to its pre-failure position in order to check the consistency of the reconstructed displacements and the initial geometric features based on 2D balanced cross-sections (figs. 7 and 8). A comparison between the results of this 3D reconstruction and previous 2D balancing has generally con-
firmed 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. 8 - 3D retrodeformation of the Como Zuccone klippe based on 2D cross-sections as in fig. 7. A) post-slip situation; B) pre-slip situation. - Retrodeformazione 3D del klippe di Corno Zuccone basata su sezioni 2D. A) configurazione attuale post-scivolamento; B) configurazione pre-scivolamento gravitativo.

GEOMECHANICAL MODELING

The following step has been the evaluation of the initial failure surface geometry and modes of failure starting from geomechanical data and specific boundary conditions. The aim is therefore the comparison of the failure surface obtained by means of mechanical modeling with that one obtained by 3D geometrical and geological modeling.

Some geometrical and geological constraints are fundamental for the numerical modeling:
- fracture systems within the DP and the ARS;
- the disturbed ARS outcrops in a slight antiformal setting;
- the geometry of the thrust plane;
- the presence of curved, almost concentric, scarps and counterscarps in the central slope sector;
- bulging and slope instability observable at the slope toe;
- the deep dissection of the Olda Unit suggesting that valley erosion was probably rapid and accompanied by a rapid stress release;
- no glacial unloading can be taken into account for the slope considered;
- the geometry of the DP block as resulting from 2D and 3D balancing.

Numerical Modelling

Physical and mechanical properties of the involved rock types are of difficult evaluation. These weak rocks present a problematic sampling especially for the highly laminated shales of the lower member of the ARS. Furthermore, very few data are available for these disconnected rock masses close to an important thrust. Data for the ARS formation have been recently collected (Barla & Naldi, 1996; Barla et alii, 1998) for the excavation of the San Pellegrino Terme tunnel and can be compared with our data set. According to these analyses (Table 1), a Bieniawski's RMR index ranging between 30 and 70 and an average Geological Strength Index (GSI) of 54 are reason-
able with an RQD value between 30% and 80% and an unconfined compressive strength between 20 to 120 MPa. Empirical relationships allow rock mass properties to be assessed from these indexes.

A distinct element model (UDEC, Itasca) has been used because of its ability in modeling the fractured carbonate block and the formation of scarps and counter-scarps. Valley erosion has been simulated by progressive elimination of thin rock blocks (fig. 9). Also the N-S compression (parallel to the adopted slope section) typical of the area has been simulated by applying a boundary velocity of about 0.1 mm/y (Westaway, 1992).

Two main processes have been observed: the valley rebound, as a consequence of unloading, and the settlement of the CZ klippe under its own weight. The maximum settlement of the DP triangular block occurs at the base of its upper half. This sagging induces the progressive flattening of the thrust plane, due to the horizontal and vertical displacement of the middle and lower slope sectors. The rebound, typical of shaly rocks (Forsyth et alii, 1975), induces an open antiformal structure along the slope and at its toe. After the sagging stage, the progressive deterioration of the ARS properties in the superficial slope sectors induce the propagation of the failure from the lower DP body toward the middle and lower slope sector. This evolution is supported by the evidence of large slope instability processes in the lower part of the slope causing the southward shifting of the Enna River. Eventually, the displacements of the entire slope during the second stage partially explain the size of the main scarp at the CZ summit.

CONCLUSIONS

The procedures used for the reconstruction of the complex 3D geological objects of the Vedeseta area enhance the possibility of using 2D GIS-related information as input data for 3D reconstruction with GOCAD. 3D surfaces have been elaborated through the reconstruction of the topographic surface interpolating a point set extracted from a DEM and subsequent attribution of elevation properties to 2D lines. Basing on the previously reported constraints, including also structural mesoscopic observations, a 3D geological model of the CZ mas-sif has been constructed, taking into account surface geology and subsurface interpretations obtained from cross-sections. Although the construction of such a model can be interpretative, due to the lack of subsurface information, a 3D visualisation of «a probable geometrical solution» gives a great help to the comprehension of the phenomenon and allows unrealistic solutions to be checked out. From a practical point of view, the geometric features of the reconstructed geological bodies can be used to design preliminary monitoring plans or subsurface investigations through seismic surveys and drillings.

The 2D and 3D reconstruction of the «pre-sliding» initial geometry of the sackung is very important for numerical modeling. For instance, two possible initial 2D assets of the klippe have been previously used (Crosta et alii, 1999) to model pre-rupture condition of the rock mass. The first model is based on a trapezoidal section of the CZ klippe, whereas the second one considers a triangular section. Basing on the geometrical 2- and 3D reconstructions carried out in this work (figs. 7 and 8), we suggest that only the second condition can be accepted (figs. 7b and 8b), thus constraining the number of the possible mechanisms. Finally, the total amount of displacement of the blocks of the klippe suggests that total deformation cannot be accommodated by plastic deformation of the lower unit and that a basal detachment must be active, as previously suggested also by numerical modeling (Crosta et alii, 1999).

The main scarp of the DSSGD, representing the superficial emergence of the failure plane, suggests - together with the graben-like structure occurring within the DP klippe - a vertical displacement of the entire slope of at least 100 m. The total displacement of the klippe may be accommodated by the southward displacement of the lower part of the slope and of the Enna River, as suggested by retrodeformation of the slide mass.

The obtained geometric reconstruction suggests that the CZ sackung is quite different from common lateral spreading. In fact, the progressive settlement of the klippe is due to sagging as a consequence of its own weight and of the sub-horizontal movement of the ARS. ARS is a hard shaly rock not presenting in the area the characteristics of an overconsolidated clay and no abnormal in situ stress have been measured in the same area (Barla et alii, 1998).

Finally, it must be remarked that even if sagging is often reported in literature (Beck, 1968; Radruch-Hall, 1978; Hutchinson, 1988; Varnes et alii, 1989; McCalpin & Irvine, 1995) in association with deep seated slope gravitational deformations, very few examples have been ever described or at least demonstrated.

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REFERENCES


Table 1

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GSI: Geological strenght index (Hoek, 1994); E: Young's modul; K: bulk modulus; m_i;: intact rock coefficient (Hoek & Brown, 1988); m_f: broken rock coefficient; S: degree of fracturing coefficient (Hoek & Brown, 1988); ψ: angle of internal friction; c: cohesion.

- GSI: Indice Geologico di resistenza (Hoek, 1994); E: modulo di Young; K: modulo di deformabilità di volume; m_i;: coefficiente per la roccia intatta (Hoek & Brown, 1988); m_f: coefficiente per la roccia fratturata (Hoek & Brown, 1988); S: coefficiente del grado di fratturazione (Hoek & Brown, 1988); ψ: angolo di attrito interno; c: coesione.


ILWIS 2.2 (1998) - ILWIS 2.2 FOR WINDOWS. ILWIS development, ITC, Enschede, The Netherlands.


