The dying town of Civita di Bagnoregio and the killer landslide

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ABSTRACT: Civita di Bagnoregio is an small village in Central Italy, located in the top of a volcanic hill and affected by continues landslides that are progressively reducing the urban area. The town was appealed as the dying town since, last century, it was believed that there were no chances to preserve this monumental landscape from destruction. The village, one of the most beautiful attraction of the region, was investigated in the last 10 years, to define a general comprehensive master plan for a restoration of town and cliffs, based on an approach capable to solve existing problems and minimizing the impact of interventions (sustainable mitigation) and continuously investigating the site as an open space geomorphological museum. Presently a small part of the cliff has been stabilized by means of new techniques from underground and a more exhaustive intervention is in progress. The present paper describe the morpho-evolutive processes of the cliff, the performed investigations, the monitoring data and the proposed solution, partially already realized.

1. INTRODUCTION AND SITE DESCRIPTION

Civita di Bagnoregio, a small village whose origin dates back to Etruscan civilisation funded in Central Italy before roman empire (about VII century BC), is located about 100 km north of Rome in the boundary between volcanic deposit of Vulsino lake and the Tiber river fluvial valley. The city, likely for military reason, is located on the top of a hill, exhibiting more than 200 m of difference in height with respect to the two E-W rivers that border the cliff in the North and South sides. Major flourishing of the municipality was in the middle age until 1695 when a disastrous earthquake destroyed most of the town and administrative and religious representatives moved to the nearby village of Bagnoregio.

Figure 1. The site of Civita di Bagnoregio

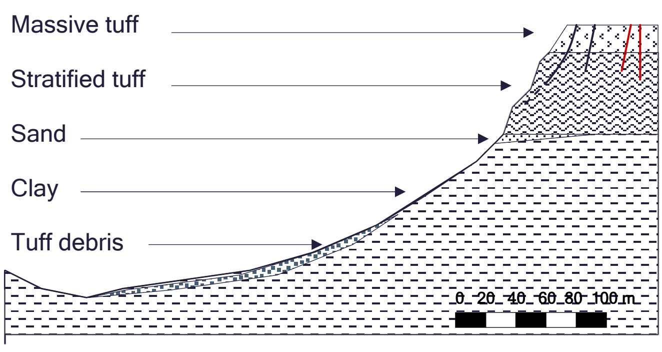

Figure 2. Geological profile of the study area

2. GEOLOGY AND GEOMORPHOLOGY OF THE AREA

The cliff where lie Civita di Bagnoregio is composed of a 20-25 m top layer of jointed ignimbrite, underlain by intensively stratified pyroclastic formation; the Quaternary tuffs rest on a bedrock of a Plio-Pleistocene clayey succession which form the valley in the major area. The clays depth can be estimated in some hundreds meters, while the outcropping portion is about 150 and 200 m in the northern and southern valleys respectively. Due to the particular geological and morphological features, the town of Civita di Bagnoregio has suffered from large and frequent slope instability phenomena (Bandis et alii, 2000): in the clayey formation landslides are represented by mudflows, debris-flows and rotational slides, while in the upper portion of the volcanic cliff, due to a retrogressive mechanism of erosion, rock-falls, toppling and block-slides are the common landslide typologies. Historical phenomena have been detected since XV c., with an almost constant number of event in the last five centuries. An edict aimed at a correct management of agricultural practices in the Civita cliffs and surroundings was also recovered in 1373. In total, about 130 phenomena has been identified from historical sources.

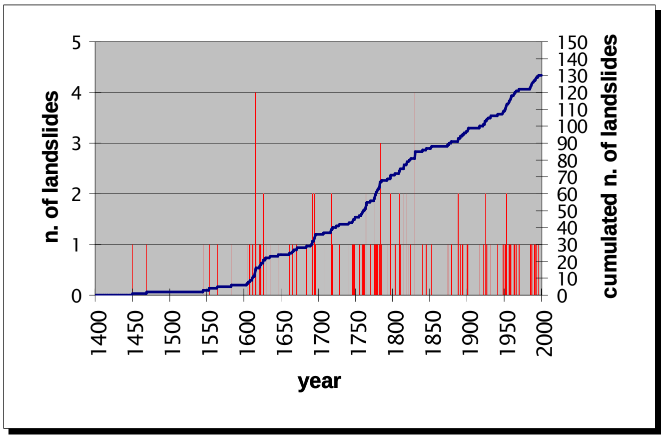

Figure 3. Historical landslide detected for the site of Civita di Bagnoregio in the period 1400-2000 A.D.

In the last decade some landslides have affected the northern border of the cliff of Civita. The rock-fall of February 1992, caused a retrogression of the scarp of 2 m, along a crown surface of about 40 m; the displaced blocks covered, in the cliff foot, a pre-existing rock-fall accumulation. Moreover, along the cliff border of new formation, in correspondence of *Piazza del Vescovado*, an opened joint, sub-parallel to the scarp direction, was observed. The joint, in W direction, intersected a building, heavily damaged, where this discontinuity appeared as widely opened and lowered. The rock-fall of August 1993 interested an area located 20 m W of the previous landslide with a scarp length of ca. 60 m. The fall involved both massive tuffs and part of the stratified pyroclastic materials, producing an average cliff retrogression of 6 m. During the previous months, in correspondence of the western side of the recently formed cliff border, an opened and lowered failure as well as local sinking were observed. Such failure represents the prosecution of the existing joint in *Piazza del Vescovado*, prolonged in W direction, under the damaged building (Fig. 4).

Figure 4. View of the northern side of the cliff and displaying of the large discontinuities.

This discontinuity was monitored since 1992 and exhibited an opening behaviour in the last decade and present day stable situation (after changing of instrument).

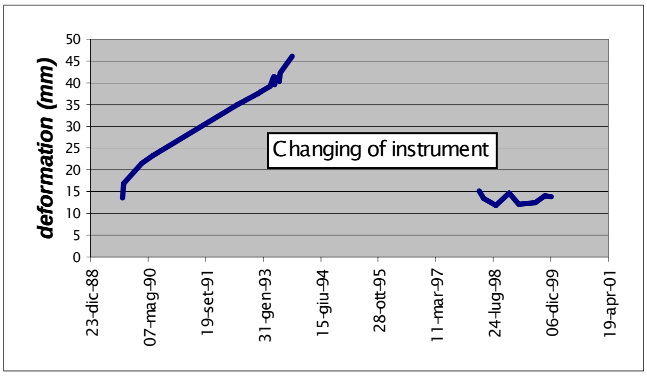

Figure 5. Deformation of the large discontinuities in the northern sector, widening in the period 1993-1998 and stable in the last two years (note, after changing instruments the “0” has been modified)

The displaced materials accumulated in the pre-existing valley below, reaching, with some isolated blocks, the bottom valley of the torrent Cireneo, at a distance of about 300 m from the cliff. The debris-flow of December 1996 re-mobilised the materials of the 1993 landslide, a small rock-fall occurred on August 1998 and a 1000 m^3 ca of a rock-fall on April 1999, that involved the stratified pyroclastic complex.

3. MECHANISMS OF SLOPE INSTABILITY

Landslide mechanism can be explicated by complex and integrated causes that, starting from the valleys erosion of water-courses, is transferred to the slopes and, then, to the cliff. Such causes can be summarised as follows:

1. deepening of bottom valleys due to runoff;
2. decaying of mechanical properties of the clays due to weathering (swelling and softening) up to an average depth of 5-10 m; in the first 0.5-1.0 m this phenomenon is more evident;
3. occurrence of mudflows with a typical 0.5-1.0 depth, after heavy rainfall, with a continuous erosion of materials and exposition of underlain layers to weathering;
4. intense superficial erosion due to weathering (some centimetres/year);
5. deformation of the clayey bedrock due to the decaying of geotechnical parameters and induction of deformation processes to the overlying tuff rocks;
6. opening of pre-existing joints in the basal stratified tuffs, due to the significant increasing of deviatory stress associated with lateral unloading, and deformation of clays;
7. opening of pre-existing failures in the upper part of the ignimbrite due to thermoclastic and cryoclastic phenomena as well as to pore pressure increase along the joints;
8. increasing of deformations in the upper part of the cliff with a progressive failure mechanism from the pre-existing joints of upper tuffs to the stratified pyroclastic materials; in the latter the straining process produce rotational failures in correspondence of plastic layers;
9. rock-falls in the upper portion of the cliff, in correspondence of massive tuffs.

Mechanisms of individual phenomena are relatively more complicated, since the slope movements are different from the top to the slope and toe of the cliff: the back analysis of historical event clearly identify crioclastic triggering factors for the 1992 rock fall, termoclastic mechanism for the 1993 rock slide (Delmonaco and Margottini, 2004), high precipitation for the 1996 debris flow. In any case, the entire process can be summarised in a cycle where rock fall, debris flow, superficial erosion, weathering and increasing of deviatory stress associated with lateral unloading and deformation of clays produce the continues slope movements.

First trigger mechanism was probably a large events that occurred in front side of the valley, dated from 14C in a tree root about 1114 A.D..

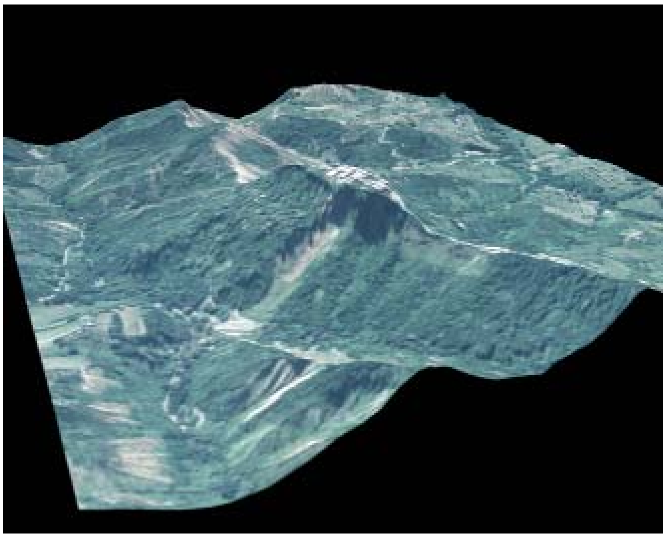

Figure 6. DEM of the area with superimposed an aerial photograph. In the left side it is possible to notice the toe of the large slide that, in 1114 A.D. moved the river from the natural linear behaviour towards the Civita cliff, Northern sector.

For this reason the town was defined by B. Tecchi, a famous Italian writer, the dying town. Today it is probably one of the best Italian geomorphological site were to study morphological processes and stabilisation measures, checking the efficacies of proposed method in really short time: in other word it is a perfect open site geomorphological laboratory.

4. GEOTECHNICAL CHARACTERISATION OF SOIL AND ROCK

Geo-mechanical properties of soil and rock have been determined from both laboratory test and back analysis of actual phenomena. In particular:

1. Massive tuff: physical and mechanical parameters are from laboratory test (Iacurto & Priori, 1995). Drop in strength it is clearly highlighted when the sample is saturated. Friction angle is referred to discontinuities and obtained from joint roughness coefficient.
2. Stratified tuff: the large variability of strata do not allow any specific laboratory test. Shear strength parameters have been obtained from the back analysis of 1993 phenomena.
3. Sand: not relevant for general stability. Phisical properties are in Cevolani et alii (1987).
4. Clay: several studies have been performed on this materials (Iacurto, 2003). Average and most reliable data have been considered in the present numerical modelling.
5. Tuff debris: shear strength paramenters are related to the contact between tuff debris and underneath clay. They have been obtained from back analysis of 1996 debris flow.

In the following table are reported the most reliable data, adopted in numerical modelling.

Table 1 – Mean properties of Civita di Bagnoregio soil and rock

	Density (kg/m^3)	Shear strength parameters (c.d.)	
		Friction angle°	Cohesion (Pa)
Massive tuff	1800	45	2000000
Stratified tuff	1900	40	800000
Clay	2100	25	100000
Tuff debris	1800	21	10000

5. HAZARD MAP AND NUMERICAL MODELLING

Mainly based on historical data an hazard map of cliff scarp was produced, according to the return period proposed by Fell (1984).

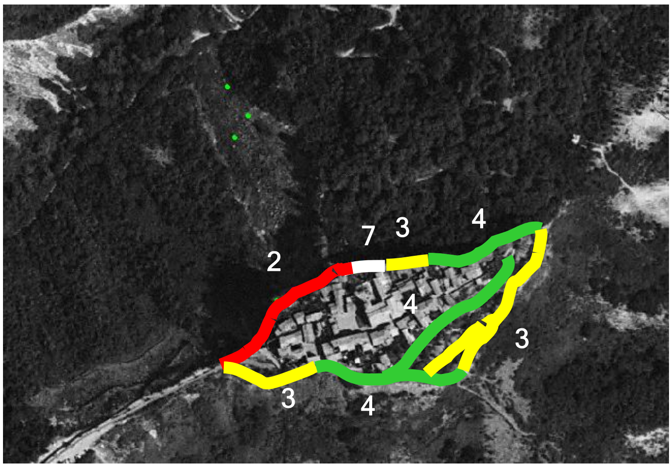

Figure 7. Hazard map of the Civita di Bagnoregio top cliff. Return period is based on Fell (1984) classification, slightly modified; 1 - Extremely high (1 per year), 2 - Very high (0.2 per year); 3 - High (0.05 per year); 4 - Medium (0.001 per year); 5 - Low (0.0001 per year); 6 - Very low (0.00001 per year); 7 - stabilized

In the area of very high hazard (*Cavon Grande* in the Northern side) numerical model has been performed to obtain a reliable information on slope stability. Investigating the possible stability conditions of cliff were computed using the explicit-difference-finite code, FLAC (Itasca Consulting Group, 2000). For given element shape function, the set of algebrical equations solved by FLAC is identical to that solved with finite element mode. Hoewer, in FLAC, this set of equation is solved using dynamic relaxation, an explicit time-marching procedure, in which the full dynamic equations of motion are integrated step by step. Static solutions are obtained by including dumping terms that gradually remove kinetic energy from the system (Dawson et. Ali, 1999).

Three major critical areas have been defined: the Cavon Grande that, after the recent rock slide of 1993 is probably retrogressing the tensioning state; the Casa Greco site where the open failure is reducing the shear strength of the cliff; the lower part of the cliff where the tuff debris laying on clay it is probably in condition of generating a further debris, when saturated.

The Cavon Grande is now exhibiting a Factor of Safety (FoS) of about 1.12 for a critical surface placed at about 30 m from the cliff border (fig. 8).

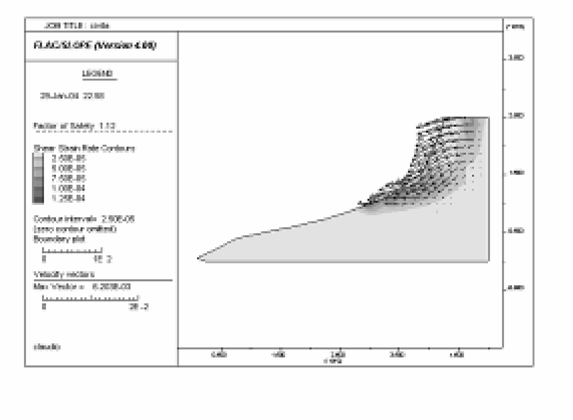

Figure 8. Shear strain rate contour and velocity vectors in a section passing thorough "Cavon Grande"

In such a situation the plasticity state show a general tendency of a upper part to a tensional state and a lower part at a shear state. This situation it is not completely reliable since the existing discontinuities, spacing about 50-100 cm, define the cliff as discontinue material and not a continue one as requested by numerical code such as FLAC. Probably, collapse may occur in smaller sub set of the cliff, not greater than 5-8 m from the scarp, as already occurred in the past.

Figure 9. The three major areas of instabilities considered relevant for the future evolution of the cliff. From top-left "Casa Greco", top-right "Cavon Grande", bottom is the tuff debris.

The site of Casa Greco is almost at the limit equilibrium. The existing open discontinuity play a remarkable role in favour of collapse and a stabilisation work is strongly required.

In the lower part of the cliff, where the tuff debris is lying over the clay, stability conditions are related to the level of water table. For a Ru ratio (height of material/height of saturated zone) greater than 0.35 the lower part of the cliff is capable to generate debris flow.

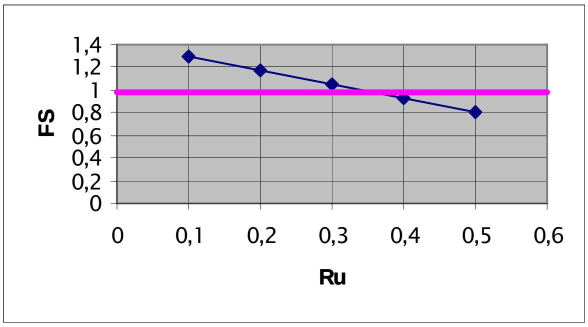

Figure 10. Factor of safety in the tuff debris for different Ru factors (Thickness of debris/width of water table).

6. THE MONITORING SYSTEM

Considering the rapid morphological evolution of the area, the Italian Minister of Education, University and Research, funded a project for the monitoring of Civita di Bagnoregio and than to provide a technological support to the consolidation strategies aimed at preventing a dramatic collapse of the cliff. The monitoring system was mainly focused to the northern cliff where majority of the problem exists. They include: 1 inclinometers (equipped with TDR), 1 piezometer, 1 3D extensometer, 2 sub-horizontal multi base bore-hole extensometer, 3 cable extensometer, 1 crack gauge, 1 meteo-climatic station, GPS network, rock noise measurement and, finally, even ground based radar interferometry. The monitoring system was installed in March 2002.

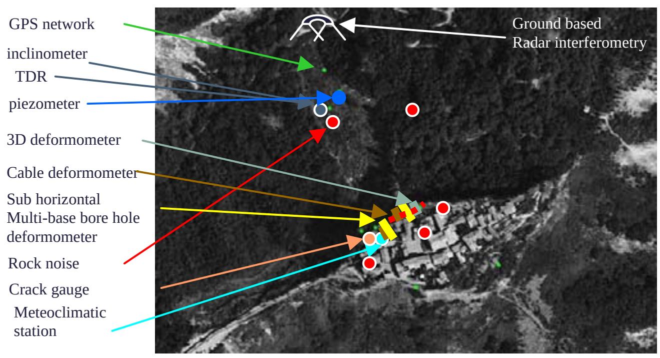

Figure 11. The realised monitoring system

Since the installation of the monitoring network no relevant displacement has been detected by the instruments. Major deformation occurred in the period 1990-1995 with the large rock slid of 1993, September 3rd.

7. THE CONSOLIDATION OF NORTHERN CLIFF

A feasibility project for the consolidation of the entire Northern sector was developed in the last years. The project was then developed according to the following purposes:

1. congruence with the available financial resources;
2. possibility to divide the global project in individual tasks, without loosing any functionality of the part already realised;
3. to solve definitively the problem of slope stability;
4. to safeguard the medium-term stability of the surrounding portions of the cliff, not directly interested by restoration works;
5. to favourite the execution of future restoration in adjacent areas;
6. to preserve the external aspect of the cliff, in respect of the landscape and historical and cultural heritage of the town.

The pilot project consider the following measurements:

1. Anchoring the upper part of the volcanic cliff (massive tuff) by means of traditional passive anchors but realised from large wells located about 6-10 m from the scarp;
2. consolidation stratified tuffs with an irregular net of micropoles (e.g. “Pali radice”);
3. protection the erosion of upper clay outcrop by means of reinforced earth;
4. Stabilisation of the tuff debris by means of large wells composed by a ring of several 1 m poles; these large wells are serving against potential deep sliding and for drainage of the debris;
5. realisation of drainage wells (sand wells and open) for the lowering of the water table;
6. mantenance of river bed;

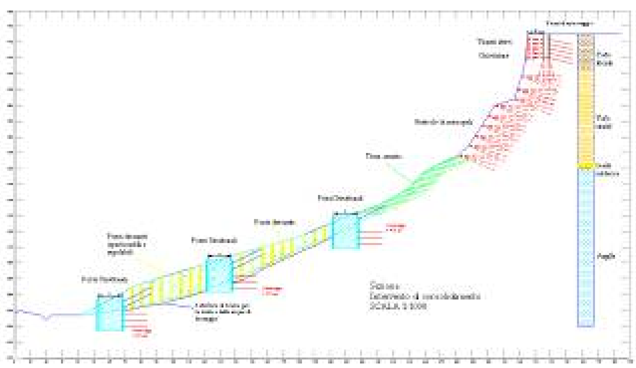

Figure 12. Typology section of the proposed intervention.

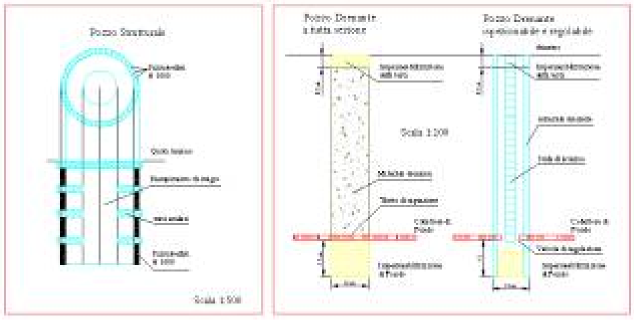

Figure 13. Detail of the proposed sand wells and open wells for the drainage of the tuff debris (redrawn from Bianco & Beligni, 1985)

According to the approaches mentioned above, a first step was already realized and reported in Bandis, (2000). The result was quite satisfactory and the mean way correctly underlined.

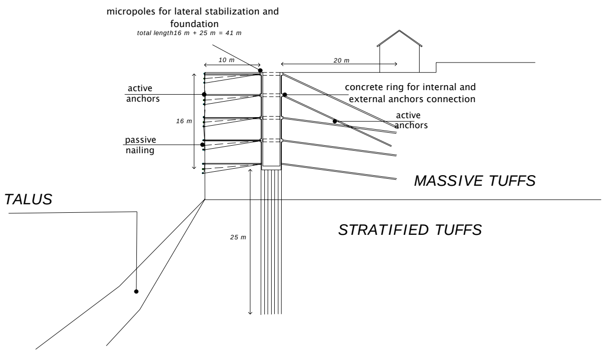

Figure 14. Detail of the already developed techniques for anchoring the upper massive tuff (Bandis et alii, 2000).

8. CONCLUSION

The pilot project in Civita di Bagnoregio, although still far from exhaustive for the resolution of the landslide problems which affect the cliff/slope system of the town, demonstrates that an effective and correct restoration may be realised in the local ecosystem, contributing to the preservation of the landscape without disfiguring the natural environment. At the same time, the conceptual solution adopted for the stabilisation of rock-falls, represents an innovative tool for the consolidation of unstable towns, mainly where geomorphological conditions do not permit any intervention from the external portion of cliffs. Finally, this experience has proved the importance to transform the comprehension of geomorphological processes into engineering projects at low environmental impact which take into account the effectiveness of works and the respect of places.

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