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Softening and swelling mechanism affecting south slope of Civita di Bagnoregio (VT)

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ABSTRACT: Civita di Bagnoregio is a small village in Central Italy, located on the top of a hill and affected by landslides that are progressively reducing the urban area. The access consists of a pedestrian bridge that connects Bagnoregio municipality to the village. The south slope beneath the bridge, is involved by frequent instability phenomena. This work describes the analysis carried out and it aimed at the definitions of geological and geotechnical mechanism affecting the above mentioned slope. A geotechnical survey has been carried out. These surveys showed the presence of a superficial layer, resulting from the softening and swelling of underlying clay-silty strongly overconsolidated, responsible for the superficial landslide phenomena. A slope stability and a 3D laser scanner model has been carried out. The analysis demonstrates that a correct design for the landscape preservation and consolidation of unstable towns needs an understanding of triggering mechanism and geotechnical properties of the involved soils.

1 INTRODUCTION

Scope of the present work is to obtain a geological and geotechnical characterization of an area, located in south side of Civita di Bagnoreggio where there is the access to the town, through the interpretation of surveys and laboratory tests. From the results is possible to obtain a geological and geotechnical model that can help to adopt technical solutions to reduce and mitigate the geomorphological hazard. The area studied is affected by a progressive erosion that, in the last 400 years, has profoundly modified the morphology, erasing a thickness of about 40 m.

Figure 1. The site of Civita di Bagnoregio.

2 SITE DESCRIPTION

2.1 *The village*

Civita di Bagnoregio (Fig. 1) is a small village whose origin dates back to Etruscan civilisation founded in Central Italy before roman empire (about VII century BC). It is located about 100 km north of Rome in the boundary between volcanic deposit of Vulsino lake and the Tiber river fluvial valley. Civita, likely for military reason, is located on the top of a hill more than 200 m respect to the Est-West level of two rivers that border the cliff in the North and Sud 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.

2.2 *Geology and geomorphology of the area*

The Civita di Bagnoregio cliff is composed by a top layer about 20–25 m of jointed ignimbrite, underlain by a intensively stratified pyroclastic formation; both volcanic layers are originated in Quaternary and they rest on the Plio-Pleistocene bedrock composed mainly of a clayey succession with a small sand levels on top, which form the valley in the major area. The clay thickness can be estimated in some hundred meters, while the outcropping portion is about 150–200 m from northern to southern part of the valley respectively (Fig. 2). Due to this particular geology and morphological features, Civita di Bagnoregio village has suffered frequently of several slope instability phenomena (Bandis et al., 2000): the mainly landslides mechanism in the clayey layer are mudflows, debris-flows and rotational slides, while the common landslide typologies in the upper volcanic portion are rock-falls, toppling and block-slides, due to a retrogressive mechanism of erosion.

Historical phenomena have been reported since the XV Century, in total about 130 phenomena has been identified with a constant rate of events occurred in the last centuries (Fig. 3).

In the last decade some landslides have affected the northern border of the cliff of Civita. Some cases are showed. The rock-fall in February 1992 caused a scarp retrogression of 2 m and 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 rock-fall in August 1993 interested an area located 20 m West of the previous landslide with a scarp length of about 60 m. The fall involved both massive tuffs and part of the stratified pyroclastic materials, producing an average cliff retrogression of 6 m. Such failure represents the prosecution of the existing joint in Piazza del Vescovado, prolonged in West direction, under the damaged building (Fig. 4). This joint is isolating a huge rock slide, that need an immediate intervention.

This discontinuity is monitored since 1992 and in the last decade present a stable situation. The materials fall are accumulated in the pre-existing valley below, reaching, with some isolated blocks, the bottom valley of the Northern torrent Cireneo at a distance of about 300 m from the cliff. The debris-flow in December 1996 has mobilized the materials of the 1993 landslide, a small rock-fall occurred in August 1998 and another a rock-fall of about 1000 m^3 occurred in April 1999 involving the stratified pyroclastic complex.

2.3 *Slope instability mechanisms*

Landslide mechanism can be explicated by a causes combination that, starting from the valley erosion caused by water-courses, has affected later

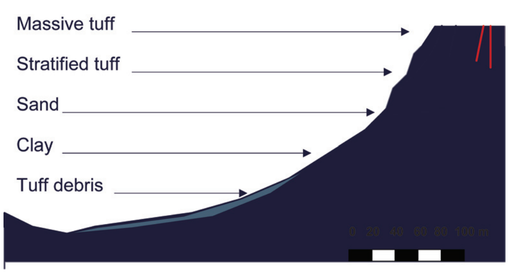

Figure 2. Geological profile of the study area.

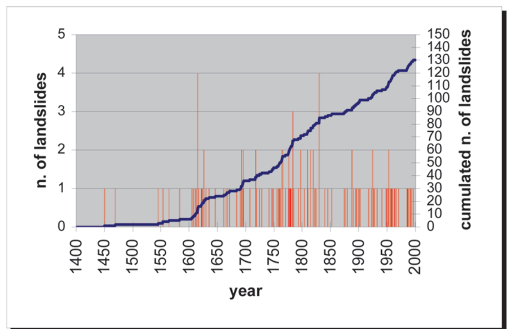

Figure 3. Historical landslide detected for the Civita di Bagnoregio site in 1400–2000 A.D. period.

Figure 4. View of the northern side of the cliff and displaying recent phenomena and the of the joints (dotts) isolating an important rock slide (red).

the slopes and, then, the cliff. Such causes can be summarized as follows:

- deepening of valley bottom due to runoff;
- decaying of the clay mechanical properties 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;
- occurrence of mudflows interesting 0.5–1.0 m depth, after heavy rainfall, with a continuous erosion of materials and exposition of underlain layers to weathering;
- intense superficial erosion due to weathering (some centimeters/year);
- deformation of the clayey bedrock due to the decay of geotechnical parameters and induction of deformation processes in the overlying tuff rocks;
- opening of pre-existing joints in the basal stratified pyroclastic formation, due to the significant increasing of deviatory stress associated with lateral unloading and clay deformation;
- opening of pre-existing fractures in the upper massive ignimbrite due to thermoclastic and cryoclastic phenomena as well as the pore pressure increase along the joints;
- 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 produces rotational failures in correspondence of plastic layers;
- rock-falls in the upper portion of the cliff, in correspondence of massive tuffs.

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 of continues slope movements can be summarized in a mix of rock fall, debris flow, superficial erosion, weathering and increasing of deviatory stress associated with lateral unloading and clay deformation.

The acceleration of geomorphological processes in the Northern cliff can be associated, likely, with a large events that occurred in other side of the valley, dated about 1114 A.D. (Fig. 5). This event, clearly visible on the field, moved the river closer to Civita, producing an higher energy relief on this part of the valley.

Due to the above processes and landslides the town was defined by B. Tecchi, a famous Italian writer, the dying town. Today it is probably one of the best Italian site to study geomorphological processes and stabilization measures, checking the efficacies of method proposed in really short time: in other word it is a perfect geotechnical laboratory.

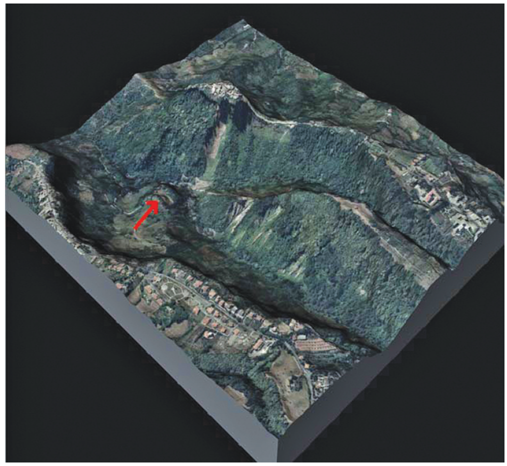

Figure 5. DEM of the area with superimposed an aerial photograph. In the left side it is possible to notice the toe of the large slide that, in 1114 A.D. moved the river from the natural linear behaviour towards the Civita cliff, Northern sector.

3 LANDSLIDES ON THE SOUTH SIDE MORPHOLOGICAL SADDLE, CONNECTING CIVITA TO THE MAINLAND

The main instability present along the slopes of the south side, subject of this study, is a phenomenon that has characterized the past evolution of this side and that was reactivated substantially in December 2008 and in March 2010 by heavy and prolonged rains reaching the current quiescent configuration as evidenced by the photographic survey follows. (Fig. 6)

Below is reported the photographic survey of the second reactivation (March 2010) and the present situation (December/January 2011) (Fig. 7).

In particular (Fig. 8), along the slopes in the south part it is present a translational mechanism type involutes in casting with speed from slow to moderate (m/year am/month) and intensity, in terms of volumes mobilized, from small to medium (from thousands to tens of thousands of m^3). With regard to the activities of these phenomena can classify them as inactive (a phenomenon that has moved the last time before the last seasonal cycle) and, within this category, identify further as quiescent.

3.1 *Saddle evolution along time*

The narrow saddle connecting Civita di Bagnoregio to the mainland was continuosly affected by soil erosion and landslides as consequence of the decay of clay materials. As a matter of fact, the following

Figure 6. Earth flows along the south slope—December 2008.

Figure 7. Reactivation flows along the south slope—March 2010 and the present.

figure (Fig. 9) is giving a reconstruction of paleo environment in the last millennium. Data are coming from a varity of sources such as archaeological, paintings and topographic measurements (Margottini, 1990).

Many historical depictions and photos are clarly showing the evolution of the saddle, as well as the

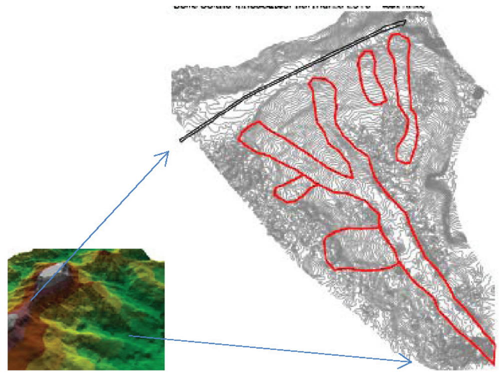

Figure 8. Earth flow instability along the south slope—March 2010.

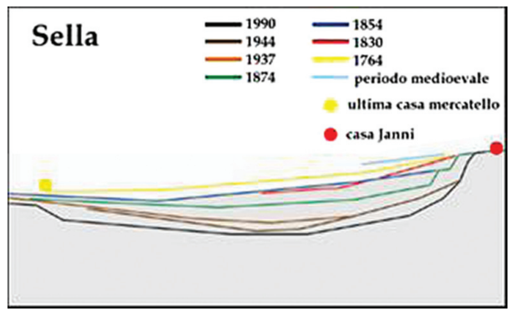

Figure 9. Evolution of the acces to Civita di Bagnoregio from medioeval time till present. Civita is on the right (Margottini, 1990, redrawn).

photos testifying the consolidation works developed along time (Fig. 10).

The instability conditions in the area (Fig. 11) are predominantly traceable to the following causes.

- The Plio-Pleistocene clays of Civita di Bagnoregio belong to the range of overconsolidated clays because in the past have been subjected to a lithostatic load greater than the current due to the weight of the overlying eroded tuff. The clay height increases towards the bottom. Such clays, especially in the most superficial parts, are subject to phenomena of swelling and softening. These phenomena produce in time the loss of resistance acquired with the preconsolidation and their behave, in term of shear strength, became that of a normal consolidated clay.
- Therefore there is a progressive loss of shear strength of soils, mainly in cohesion component, due to the pore pressure/interstitial related to the circ-lation of water, especially in the surface layer with a thickness ranging from 1.0 to 2.0 m.

Figure 10. Civita di Bagnoregio access morphological saddle: anti-erosional works in 1948.

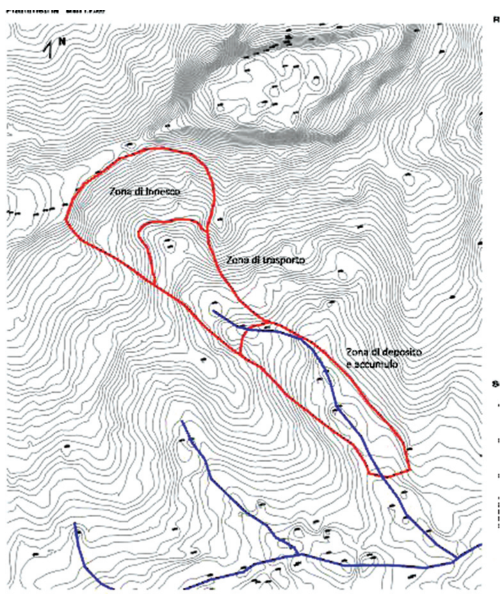

Figure 11. Geomorphological zoning of the southern part of the saddle, in terms of source, transportation and accumulation for triggered earth flow.

- Absence of a controlled drainage network, which produces a general infiltration of water in the cluster and a runoff concentrated in some sectors of the slope toward the higher part of the valley.

4 SURVEYS

4.1 *Laser 3D*

On 14 December 2012 was carried out by the Survey Lab staff, Spin Off of the Department of Civil Engineering, Construction and Environmental Engineering of "Sapienza" university—Area of Geodesy and Geomatics, a detailed survey of the landslide in south part of Civita di Bagnoregio.

As noted during the inspection, the side affected by instability looks just vegetated in the upper part, with a forest cover that increase going towards the valley. The gradient of the slope and the characteristics of the soil permit a relief with traditional topographic instrumentation. In particular, a digital model of the surface (DSM) has been extracted from the digital map, which form the basis for the detailed design of the safety measures. The survey was carried out by integrating the use of a Terrestrial Laser Scanner for three-dimensional reconstruction of the slope and methodology of GNSS (Global Navigation Satellite System) for placement in the existing maps. The use of laser scanner has allowed to obviate in part to the presence of vegetation; in fact the ability to acquire a large number of points (in the order of 106) with a minimum error on the determination of the position (a few cm to 100 m distance) permit to discriminate between ground points and vegetation points. From the point cloud data obtained was then eliminated, where possible, vegetation to reconstruct the exact morphology of the slope. The positioning of the relief in local mapping was performed using GNSS receivers geodetic mode RTK (Real Time Kinematic). From digital surface model was extracted digital mapping of detail contour, with spacing of 1 m, set within the frame of reference UTM-WGS84, with quotas related to sea level (Fig. 12).

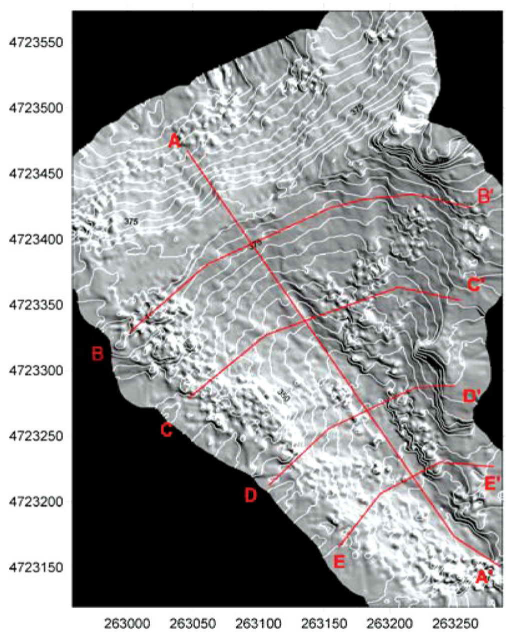

Figure 12. Digital elevation model of the area of the south side with overlapping contours (spacing 5 m) and showing the position of the sections produced.

4.2 *Soil investigation*

In December 2011, a new surveys campaign was performed on the area of intervention. The mainly aim was know the thickness, physical and mechanical properties of the material involved in the landslide of 2008 and of 2010.

The location of the surveys (Fig. 13 and 14) was chosen for the better layer representativeness in terms of geotechnical parameters, compatibly to the places accessibility.

The choice of the investigation was influenced by the presence of trees, slope steepness and instability that did not allow the use of heavier equipment.

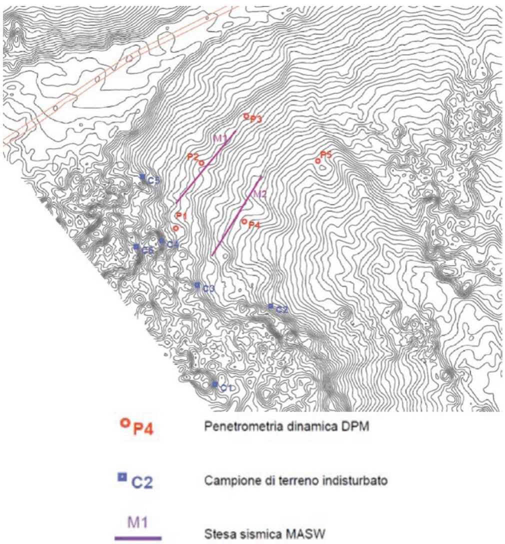

Figure 13. Geognostic surveys location—December 2011.

The surveys campaign included the following tests:

- 5 DPM penetration tests;
- 6 samples taken manually from trial pits for laboratory testing;
- 2 MASW.

Important informations concerning the thickness of potentially mobilizable can be deduced from the five penetration tests. All penetration tests show a trend rather homogeneous, it is possible to distinguish the superficial layer, resulting from the softening and swelling of underlying clay-silty strongly overconsolidated, is ranging from 1 to 2 meters (tests P1, P2, P4) to a maximum of 3 meters (P3 and P5) (Fig. 15).

As regards the seismic profiles (Fig. 16) the first variation of the waves speed is observed for a seismo layer attested to the depth included between 2 and 3 meters in agreement with the results of the penetration tests. By the two seismic profiles are clearly specified the presence of a portion of superficial layers with a low consistency resting on a more rigid layer to a 15 m depth. It is evident the presence of two inconsistent layer who can represent slide planes (Fig. 17).

Samples were taken at different stratigraphic altitudes in order to characterize the yielding levels. Sampling was done with a Shelby sampler, ϕ 100 mm and L 200 mm.

On samples were performed the main laboratory tests to estimate the geomechanical parameters with direct and anular shear tests. The following table shows the main parameters (Fig. 18). From samples taken can be seen the low effective cohesion value of the superficial layer, this shows the effect of swelling and swelling of this layer and the

Figure 14. DPM penetration tests: site not easily accessible.

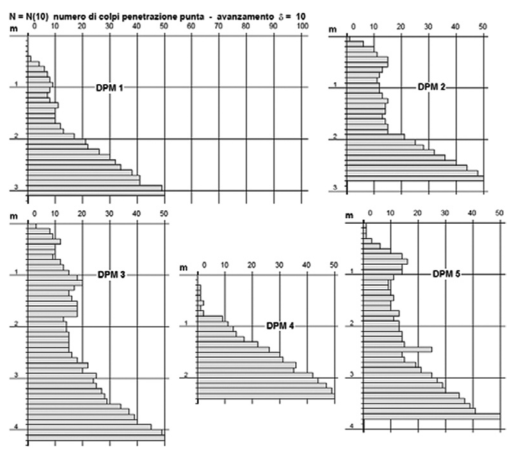

Figure 15. DPM elaboration.

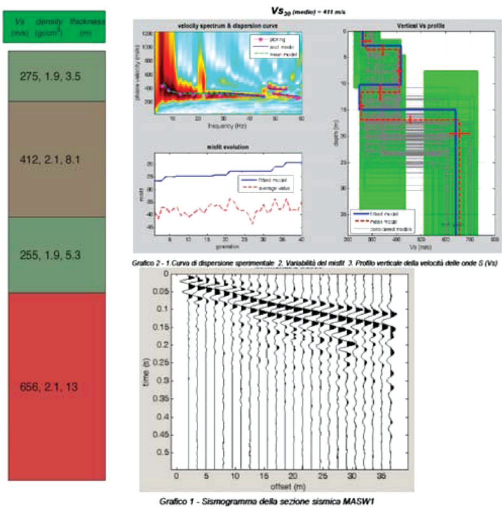

Figure 16. Seismic parameters elaboration derived from MASW test.

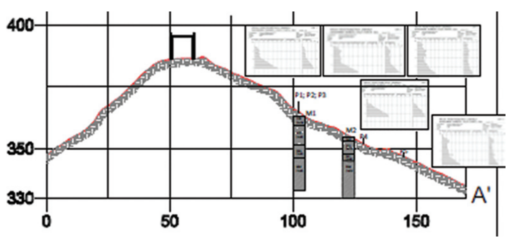

Figure 17. Geotechnical section along the southern side from penetrometric tests and MASW.

Certificato n°	Sond. & Camp.	Prof. (m)	W %	γ_{nat} kN/m³	γ_s kN/m³	e	L.L. %	I.P.	c' kPa	ϕ' °	c'_r kPa	ϕ'_r °
5906	S -- C 1	00.20 --	26,7	18,91	27,28	0,828	53	26	2	22	0	22
5907	S -- C 2	00.20 --	23,6	14,37	25,59	1,201	43	18	0	29	--	--
5908	S -- C 3	00.20 --	24,9	19,06	26,06	0,708	42	18	6	25	0	24
5909	S -- C 4	00.20 --	23,3	15,64	26,47	1,087	52	26	8	24	0	24
5910	S -- C 5	00.20 --	33,2	16,07	26,61	1,206	56	27	2	27	0	26
5911	S -- C 6	00.20 --	24,3	19,47	26,67	0,703	45	26	4	25	0	21

Figure 18. Geotechnical parameters summary.

high grade of erosion suffered. Moreover the coincidence between the effective angle and the residual angle says that this layer is in a quiescent state due to a remobilization (landslides) in the past.

5 CONCLUSION

The study performed has allowed the reconstruction of the morphology before and after the landslide, the identification of potential slide plane, the parametric characterization of layers and the substrate.

From surveys carried out and from the geotechnical characterization was verified, visually and analytically, the state of evident degradation that characterizes the study area and has been possible reconstructed the local geological and geotechnical model.

The causes of decay are numerous and include increased erosion superficial, the changing of rainfall resulting from climate changes (heavy rainfall concentrated in short periods of time), decreased water retention by the soil that prevents the infiltration of natural waters of precipitation. For the resolution of these problems can be necessary to create an integrated intervention, a multi-disciplinary, can substantially mitigate the impact of dynamic geomorphological and climatic conditions which have led to the state of the general deterioration of the area.

Thanks to the specific field and laboratory investigations which were carried out it was possible to develop a working plan that offers long-term solutions, to eliminate the hydrogeological conditions that characterize the area of the southern slope below the access bridge into the town of Civita di Bagnoregio.

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