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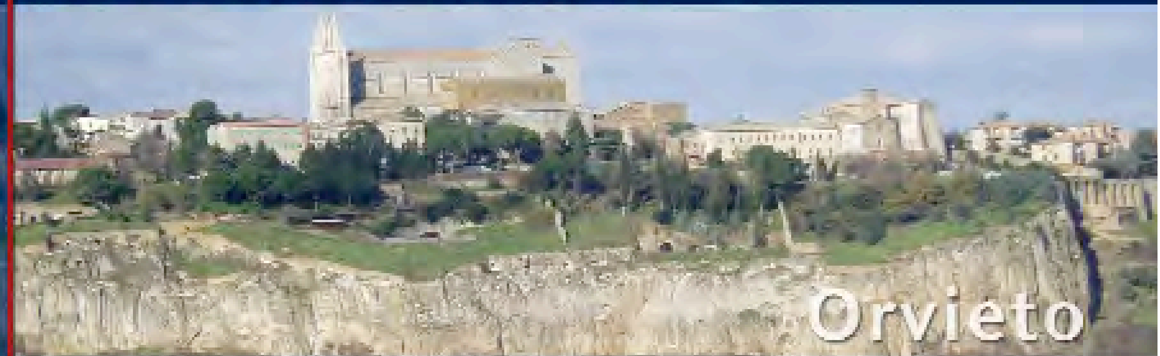
FIELD TRIP GUIDE BOOK

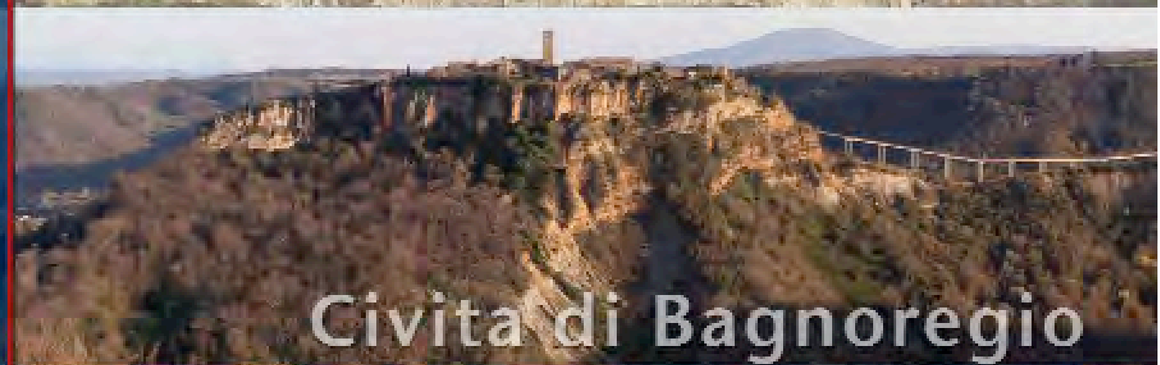
THE SECOND WORLD LANDSLIDE FORUM

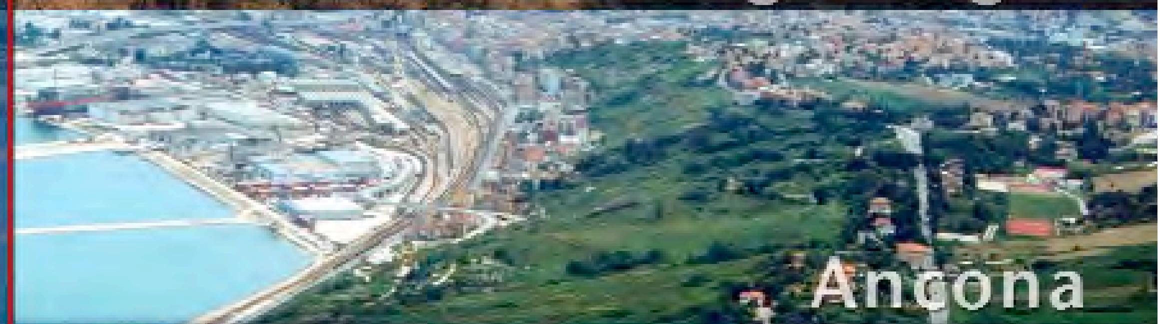
3|9 October 2011 - Rome

Field trip to Orvieto, Civita di Bagnoregio and Ancona

an itinerary through landslides, cultural heritage and innovative solutions for monitoring







G. Delmonaco - G. Scarascia Mugnozza - P. Tommasi

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Giuseppe del Monaco, ISPRA, Rome
Gabriele Scarascia Mugnozza, Università "Sapienza", Rome
Paolo Tommasi, CNR-IGAG, Rome

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Field trip of the
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Paolo TOMMASI (CNR-IGAG)

Front cover *(from the top to the bottom):*

Aerial view of the southern cliff of Orvieto before the stabilization works. In the foreground an old failure at the cliff margin and in the clay slope below. In the background the impressive cathedral

View of the Northern unstable slope of Civita di Bagnoregio from Lubriano

Aerial view of the Great Landslide (1982) of Ancona towards the seafront

Field trip to Orvieto, Civita di Bagnoregio and Ancona
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Field Trip | October 1-2, 2011

Authors:
Giuseppe Delmonaco, ISPRA, Rome
Gabriele Scarascia Mugnozza, Università "Sapienza", Rome
Paolo Tommasi, CNR-IGAG, Rome

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INTRODUCTION

The main objective of this field trip is to insert the visits to landslides within a frame where a mix of history, cultural heritage and technological developments for monitoring play a crucial role.

Within such a context, the participants will be introduced to world famous historical sites threatened by landslides and will appreciate the different perspectives and solutions adopted to cope with landslides, due to their different dimensions, mechanisms and characters, as well as urban conditions.

In Orvieto we will show "standard" remedial measures taken in case of a tuff cliff subject to failures and undermined by landslides in the clay slope below.

In Civita di Bagnoregio we will see a unique example of erosion and landslide processes which isolated a small cliff where the so-called "dying- town" is founded. In this case, innovative structural remedial measures have been adopted.

In Ancona an example will be given of a different approach based on the concept of mitigation through continuous topographic and geotechnical monitoring and management by an Early Warning Centre.

ORVIETO

THE LANDSCAPE FROM ROME TO THE NORTH

The highway to Orvieto, soon north to Rome, winds within the Tiber River valley which is bounded by the steep margin of the volcanic plateaux to the west, and the counterforts of the Apennine chain to the east (**Fig. 1**).

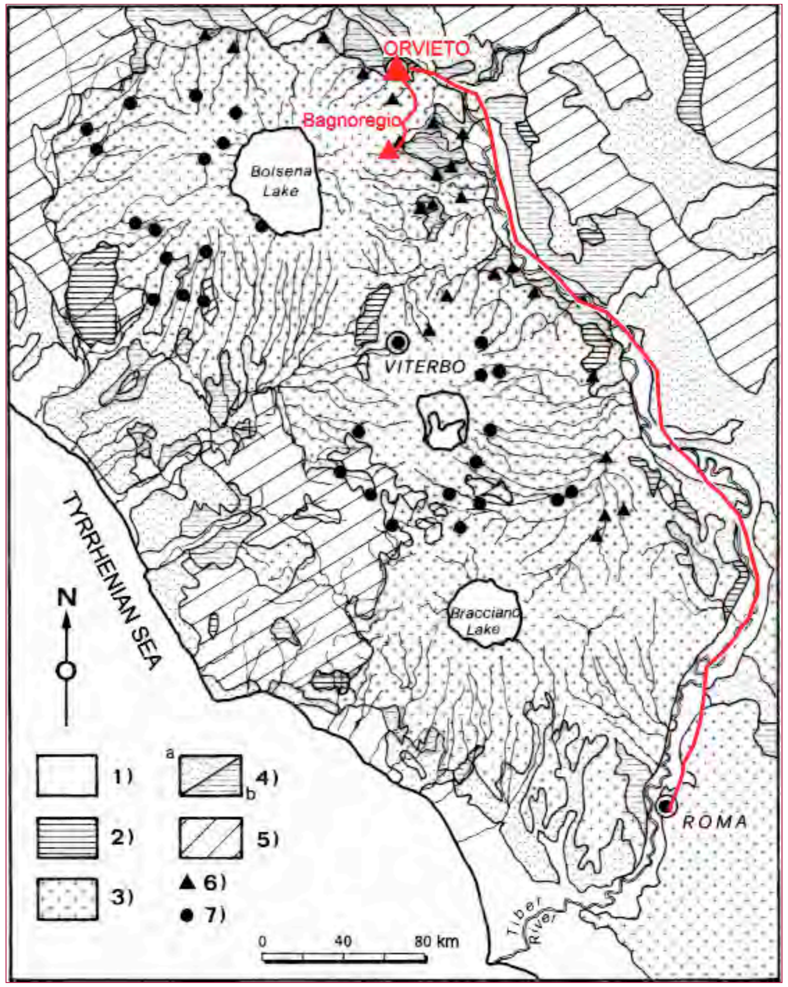

Fig.1. Schematic geological map of the northeast area of Rome: 1) alluvial soils; 2) travertines; 3) volcanic formations; 4) Plio-Pleistocene sandy-gravelly (a) or clayey (b) sediments; 5) Meso-cenozoic basement; 6) towns rising on rock buttes overlying Plio-Pleistocene sediments; 7) towns rising on rock buttes overlying volcanic formations. (From Ribacchi et al. 1998). In red the travel itinerary from Rome to Orvieto and Bagnoregio

THE SECOND WORLD LANDSLIDE FORUM

Along the margin of the plateau, several ancient hamlets and towns overlook the valley, from the top of buttes, mesas and inselbergs isolated by the erosion. These isolated hills generally are formed by pyroclastites and lavas erupted by the four main volcanic apparata of Northern Latium since Early Pleistocene. At times volcanic rocks are replaced by travertines deposited in lacustrine environments set before the erosive phase. Erosion is accelerated and morphologies are sharper where the Plio-Pleistocene clayey formation, underlying the volcanic plateau, crops out. This occurs at the plateau margin and along the deepest and narrowest valleys of the right tributaries of the Tiber River.
The historic towns of Orte, Mugnano, Bomarzo (with its giant monsters carved by renaissance sculptors directly into welded tuff boulders fallen from the plateau cliffs), Bassano, Castiglione and, eventually, Orvieto progressively appear along the western valley flank.
Ribacchi et al. (1988) pointed out that instability phenomena have much larger extension, diffusion and frequency where the sedimentary substratum crops out for a significant height below the cliff foot (especially if clayey) (towns with triangles in **figure 1**) rather than on slopes entirely formed by volcanic formations (towns with full circles in **figure 1**). Two typical examples of the former situation are Orvieto and Civita di Bagnoregio. Although these two sites have similar geotechnical stratigraphy and instability mechanisms, Civita is characterized by a much more accelerated erosion entailing higher landslide susceptibility and reduced possibility/effectiveness of hazard mitigation.

GEOLOGICAL FRAMEWORK

Fig. 2. View of the southern cliff of Orvieto from the Badia (Stop 1) before the completion of stabilization works. Systematic vertical joints are visible

Orvieto (**Fig. 2**, **Stop 1**) is a major historical town endowed with an inestimable artistic heritage dating back to the Etruscan period. The ancient town was built on the top of an elliptical slab (1500 m 700 m) delimited by vertical cliffs up to 60 m high, which is formed by the "Orvieto and Bagnoregio Tuff", a pyroclastic formation erupted by a centre of the Bolsena volcanic district about 330,000 years BP,

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consisting of lithic tuffs and a moderately coherent facies (pozzolana). The slab overlies a roughly tronco-conical base, formed by an overconsolidated stiff clay, with gentler slopes (with an average gradient varying from 12° to 18° for the northern and southern side respectively) covered by slide debris. The clay slope is furrowed by five gullies which depart radially from the cliff foot.
Interposed between the two formations is a succession of 3–15 m of weakly cemented, fluvial-lacustrine coarse-grained and silty materials, which hosts a perched groundwater.
The in situ clay formation is blanketed by an irregular layer of slide debris which consists of remoulded clay irregularly overlaid by a layer of pyroclastic materials from 0.5 m to 5 m thick (**Fig. 3**). At depth, the in-situ clay is stiff and apparently intact, but proceeding upwards, it progressively softens and becomes more and more fissured and even jointed; nevertheless stiffness and undrained strength remain quite high. Small-scale softening is evidenced by natural water content and undrained strength whilst fissuring/jointing are well evidenced by shear wave velocity. Thicknesses of the softened clay and of the debris cover vary throughout the whole slope.

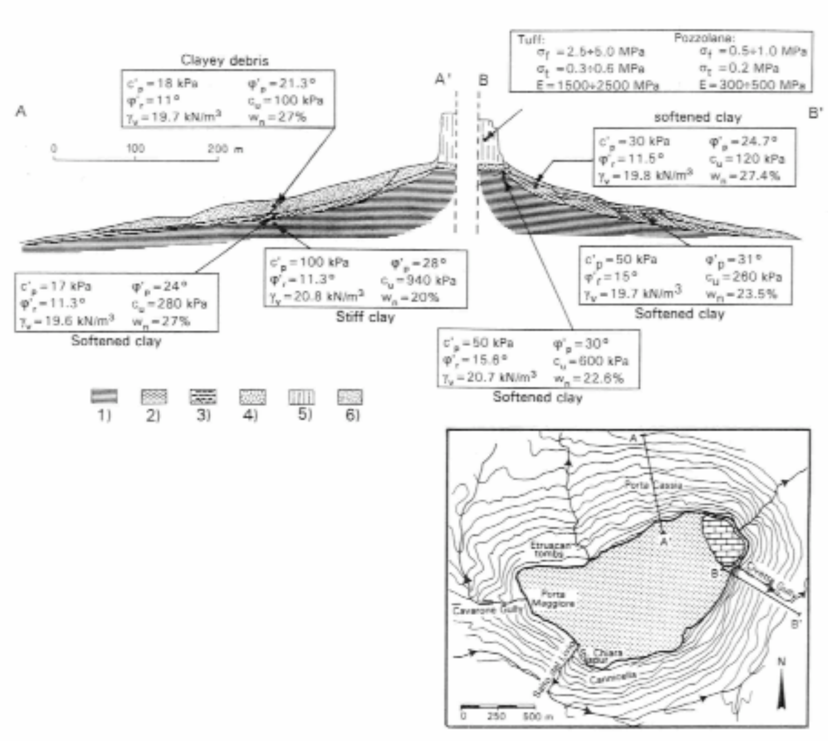

Fig. 3. Schematic geotechnical profiles across the entire Orvieto hill with mechanical properties of materials involved in the instability phenomena. 1) stiff clay; 2) softened clay; 3) remoulded clay (claeyey debris); 4) fluvio-lacustrine formation; 5) pyroclastic slab; 6) landslide debris formed by remoulded clay and pyroclastic material (after Tommasi et al 1996)

GEOTECHNICAL PROPERTIES OF THE MATERIALS

Clay formation and debris cover

The clay material is a clay and silt of medium plasticity which remains homogeneous throughout the whole slope. The undrained strength increases with depth from 0.3 to 0.6 MPa within the softened portion, whilst it exceeds 1 MPa at a depth of 35 m.
Softening largely affects also shear strength and stress–strain behaviour of the clay material. The softened clay has reduced stiffness and brittleness (Tommasi et al. 1996) which however remains high. Similarly to other stiff clays (e.g., Rampello 1991) softening implies a significant decrease in effective cohesion *c'* and, at times, in friction angle *0*ϕ'. Effective cohesion, *c'* which is equal to 100 kPa for the intact clay, in the softened clay drops to 30 kPa in slide areas and to 60 kPa in less disturbed areas . In slide areas also a significant decrease in friction angle from 30°-32° to 24°-27° was detected.
The clayey portions of the slide debris are formed by a remoulded clay material whose grain size and plasticity are similar to those of the underlying in-situ clay. Remoulding cancels effects of overconsolidation so that the material exhibits a linear increase in undrained strength up to 0.3-0.4 kPa depending on the maximum depth of the debris cover. Effective shear strength is much lower than those of the softened in-situ clays both in terms of cohesive (*c'*= 18 kPa) and frictional (ϕ'= 21°) components.
Since all clay materials (intact, softened and remoulded) have quite similar intrinsic properties, a unique residual shear strength angle can be assumed, which ranges between 11° and 13°.

Pyroclastic materials

Even though both lithic tuff and pozzolana have high porosity (46-57 % and 52-59%, respectively), the former is much stiffer and strong as an effect of the higher continuity of the glassy structure and widespread growth of zeolite crystals which fill pores.
The lithic tuff facies actually includes different lithotypes whose average uniaxial compressive strength and indirect tensile strength in dry conditions vary in the ranges 3.5-4.8 MPa and 0.45-0.65 MPa, respectively (Tommasi and Ribacchi 1988). Uniaxial compressive strength, σ_c, and indirect tensile strength, σ_t, of pozzolana are

much lower (Tommasi et al. 2006): 0.9-2.5 MPa for σ_c and 0.05-0.12 MPa for σ_t. Pyroclastic materials are chacacterised by a sharp curvature of the strength envelope and low values of yielding mean stress p_y under isotropic state of stress; however sharp differences between the tuff and the pozzolana were found also in triaxial conditions. In the plane of principal stresses, the strength envelope of the tuff lies significantly above than those of the pozzolana and p_y passes from 6-9 MPa for the tuff to 3.7MPa for the pozzolana. Similarly, the tuff maintains a brittle behaviour at confining pressures which are much higher than those observed for the pozzolana (0.8-3 for the tuff vs. 0.15 for the pozzolana).

INSTABILITY PHENOMENA

The rock slab

Fig. 4. Backward-tilted Etruscan dice-tombs of the necropolis of "Crocifisso del Tufo" on the northern slope (Stop 2). The terrace in the foreground is horizontal

Major instabilities phenomena at the slab margin are represented by the lowering of large blocks (up to some thousands of cubic meters) and "slices" delimited by vertical fractures. Slices can be as high as the cliff, up to few tens of meters wide and some meters thick. Fractures were induced by the severe state of stress at the slab margin caused by the interaction between the rigid slab and the deformable substratum in response to the intense erosion which dismantled the pyroclastic formation and the underlying clay. Blocks can either topple or, more likely, slump

as demonstrated by the backward-tilted Etruscan tombs of the necropolis of *Crocifisso del Tufo* (**Fig. 4**, **Stop 2**). Otherwise they progressively and pervasively fracture until collapse.

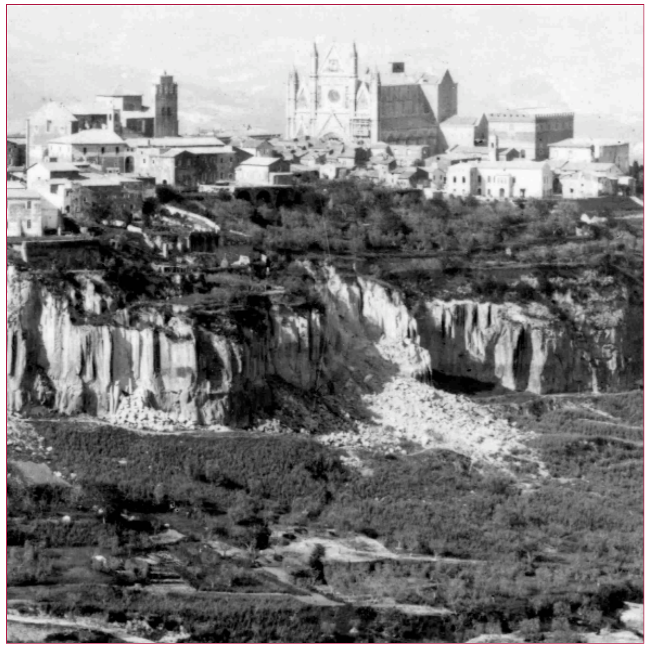

Fig. 5. Collapse of a tuff spur occurred at the very beginning of the 20th century underneath the Convent of SantaChiara, on the southern cliff. Failure of slices are visible on the left of the major collapse.

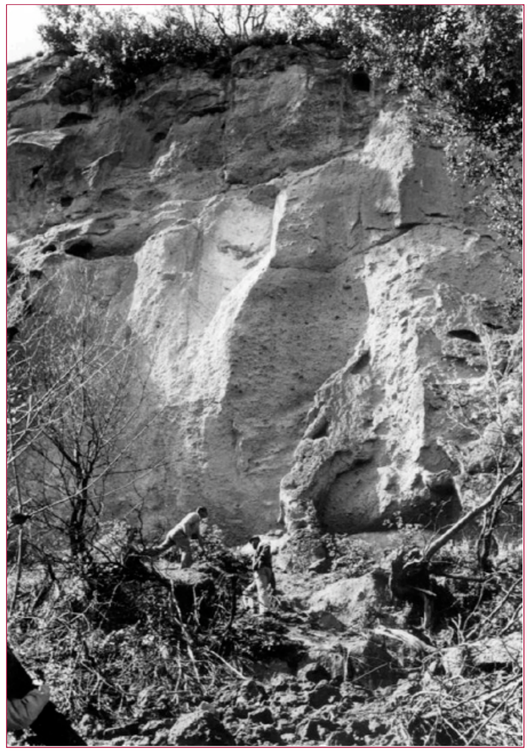

Fig. 6. Failure of a high slice of pozzolana delimited by irregular fractures, occurred on the southern cliff in 1984

A dramatic example of this instability mechanism is shown by the rock spur hosting the Santa Chiara Convent which across 19th-20th centuries was partially demolished by a sequence of large rock slides (**Fig. 5**) (Tommasi et al. 1996). In the pozzolana facies, failures involving several hundreds of cubic meters over the whole cliff height, occur along irregular surfaces (**Fig. 6**).

Much more frequent are falls of small wedges consequent to toppling and sliding of columns or failure of the intact rock. This usually occurs in shear (at the base) or in tension (at larger height), often favoured by the static fatigue. A number of minor causes as ice or root expansion in fractures trigger definitely the rock fall.
Failures on the cliff have been locally influenced by the instability of the underground cavities which were excavated since the Etruscan period at different elevations (often superimposed) throughout the whole pyroclastic formation (**Stop 3**). Cavities were excavated for the extraction of pozzolana (room and pillars quarries closed by mining authorities at the beginning of 20th century), pigeon keeping (*culumbarium*), storage of goods/liquids, olive oil pressing and flour milling. At present, many cavity vaults and pillars are seriously damaged (**Fig. 7**) so that their failure can damage roads and buildings or trigger instability phenomena on the cliff when cavities develop underneath the slab surface or behind the cliff, respectively.

Fig. 7. Picture of a vault collapse in an underground cavity close to the cliff wall, near the St.Francis (o San Francesco) Church (Stop 3) taken before the reinforcement and rehabilitation works.

The clay slope

The clay slope typically evolves through multi-storied landslides (Hutchinson 1988) both in the form of failures and slow movements directed along the dip direction of the slope. Relatively shallow slumps also occur on the banks of the gullies which in the course of time have been progressively deepened by the erosion produced by the increased waste water flowing within them.
Deeper (and larger) instabilities consist of extremely slow translational movements along well defined shear surfaces or bands extending from the slope toe up to the upper third of the slope (at times up to the foot of the cliff) within the softened portion of the "in situ" clay formation (down to the depth of 35 m) (**Fig. 8**). These movements, proceeding at an average displacement rate lower than 3 mm/year (Tommasi et al. 2006), are likely to represent a very advanced evolutionary stage of old failures that started under quite different morphologic conditions and propagated retrogressively. Documented evidences of large failures are found in the form of scarps and terraces still having a sharp relief and large extension (Manfredini et al. 1980).

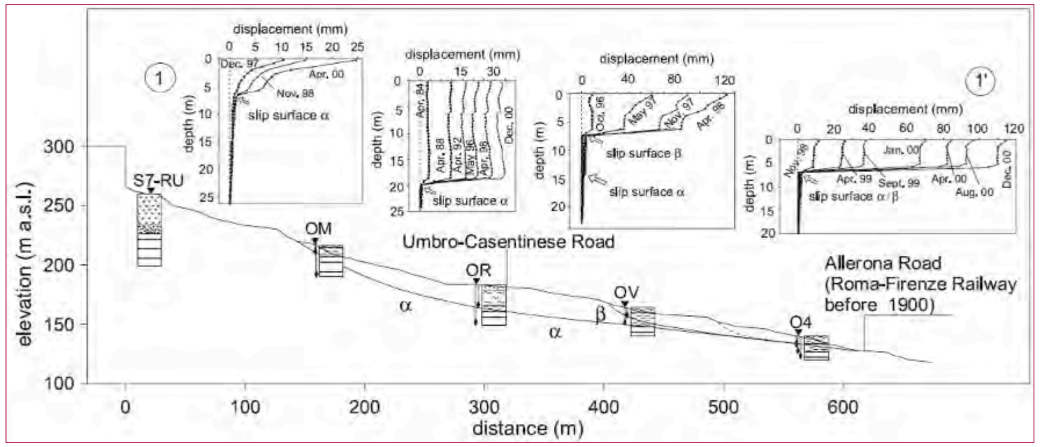

Fig. 8. Slip surfaces detected through displacements monitoring through probe inclinometers: a surface related to deeper movement within the softened clay; b surface related to shallower movement within the slide debris (after Tommasi et al 2006, modified)

Superimposed to these movements, within the remoulded slide debris, translational movements occur at higher displacement rate (average recorded 35 mm/year). Even though shallow movements do not produce any disruption of the sliding mass and fall within the "very slow" class of Cruden and Varnes' classification, they are however responsible for serious damages to buildings and infrastructures. Furthermore they contribute to the general mechanism which in the long-term leads to the instability of the slab margin.
Slope failures are not only recognizable from morphological evidences but have also been directly observed or documented. Deeper failures were reactivations of old movements caused by major man-made changes in slope geometry (slide of *Porta Cassia* in 1900 on the northern slope, according to Diamanti and Soccodato 1981) or by the increase in piezometric level caused by indiscriminate discharge

of waste water on the slope (slide of *Cannicella* in 1979 on the southern slope according to Manfredini et al. 1980). Shallower failures have mainly affected the gully banks and at times involved the debris cover in other areas of the slope.

MECHANISM OF INSTABILITY

The instability of the rock cliff is the result of failures, movements and deformational processes in the clay slope, localized within the upper softened portion of the clay formation and the clayey slide debris. These are mainly caused by the softening of the clay formation induced by the erosion. In fact, softening sharply reduces the shear strength of the clay formation down to a significant depth both along the clay slope and underneath the cliff foot.

The erosive processes, in conjunction with the strong stiffness contrast between the slab and the clay formation, is also responsible for the anomalous intense fracturing of the rock mass up to 15-20 m behind the cliff face.

This mechanism is supported by the results of finite element stress-strain analyses (Cecere and Lembo-Fazio 1986) simulating the erosion of the hill. Analyses indicate that erosion induces yielding in shear in the clay slope and tensile stresses at the slab margin which are higher than the tensile strength of the pozzolana and of some tuffaceous facies.

The fractured portions of the slab margin are deprived of support by the relentless movements in the clay formations, which also displace the talus debris thus vanishing its confining action. Under these conditions, slices and blocks can experience large displacements, further jointing and eventually the collapse. This process is accompanied by minor failures, with different mechanisms, of columns and wedges isolated by the network of joints induced by the main instability mechanism described above.

SLOPE STABILIZATION AND MITIGATION MEASURES

Remedial measures, in the modern sense, started in the Renaissance (Tommasi et al. 1986), when the town expanded up to the cliff margin and engineers/architects of the Pontifical State were involved in public works (Margottini and Martini 1999). Until 1960 they were prevailingly aimed at preventing failures on the cliff which represented the most tangible threat to inhabitants and buildings. This scope was pursued, even though different materials and construction techniques, through retaining, lining and underpinning walls and through scaling of the most loosened portions of the cliff. Since 70's rock reinforcement, which before had consisted only of column bracketing, was introduced through passive bars, moderately prestressed bars/cables and injections aimed to fracture sealing.

In 1980, following to a series of failures on the cliff and on the clay slope, a special law for the preservation of Orvieto was promulgated by the Italian Parliament. The law envisaged a considerable funding which was extended over about twenty years. The programme of stabilization and mitigation works was directed both to the rock cliff and to the clay slopes. The latter scope was pursued through a series of measures that were all mainly addressed towards the reduction of pore pressures in the slope:

- elimination of uncontrolled water discharge onto the clay slope;
- elimination of leaks from sewer and aqueducts, which had increased infiltration in the pyroclastic slab;
- regulation of hydraulic regime of gullies and stabilization of their banks (**Fig. 9**);
- drainage in critical areas of the slope through horizontal drains drilled from shafts.

Fig. 9. View of the Salto del Livio Gully (southern cliff) during the regulation works (1985)

Control measures in the clay slopes were aimed to prevent failures and slow down movements within the debris cover. Deeper movements were not taken into consideration due to the impossibility of reducing pore pressure at the sliding depth. Actions aimed to limit the infiltration have however demonstrated to be effective in the areas that had been repeatedly involved in failures with slip surfaces within the softened part of the clay formation.
Stabilization of the cliff was carried out through a virtually systematic reinforcement of the shallow portions of the rock mass by means of passive bars and anchoring of the potentially unstable wedges by means of moderately pre-stressed tendons (Fig. 10). A major task for the future will be the maintenance of the control measures whose decay was described in the past by authorities in charge of the preservation of the hill.
The stabilization works have been accompanied to a monitoring programme including probes and fixed-in-place inclinometers and piezometers in the clay slope as well as borehole extensometers in the rock mass. Instrumentation, installed over the whole perimeter of the hill with special reference to some “critical” areas, is read periodically by a local survey office (*Osservatorio della Rupe di Orvieto)* which continuously updates a database used for data management and decision making by regional and local authorities.

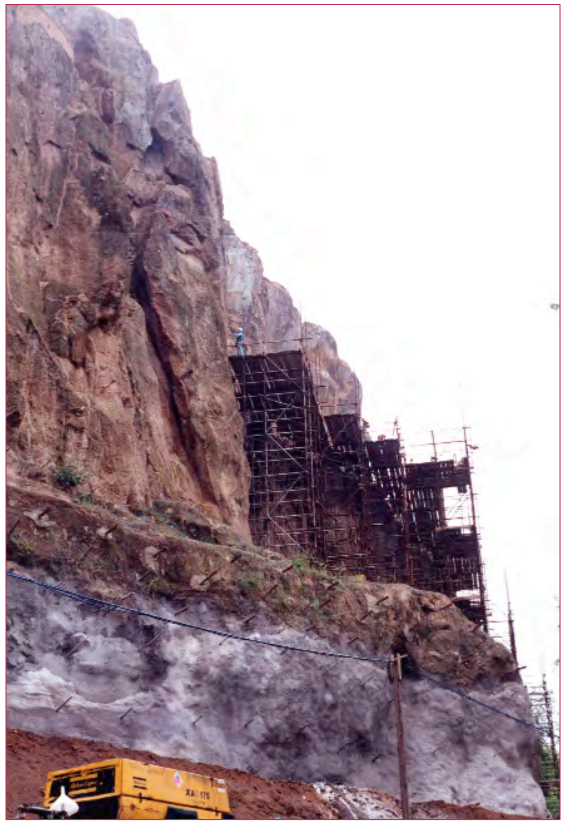

Fig. 10. Works for the reinforcement of the northern cliff. Passive bars are visible in the slightly cemented pyroclastites and fluvio-lacustrine sediments at the cliff base. Scaffoldings for drilling and installation of pre-stressed tendons and passive bars are visible on the cliff. Formed by lithic tuff. In the foreground a potentially unstable large wedge anchored on the rock mass is visible.

Stop 1

***Abbey of SS. Severo e Martirio* (*Badia*). View of the southern cliff of Orvieto. In the central part, underneath the imposing Cathedral, the superimposition of the Pozzolana facies to the lithic tuff is apparent together with the typical subvertical jointing. On the left a landslide scar and the related debris fan caused by a collapse of a rock spur are visible. On the left of the scar a spur significantly lowered with respect to the surrounding slab can be noticed. On the right an old long counterfort retaining wall supports the access road to Orvieto. Below the pyroclastic slab the terraced morphology of the clay slope due to the repeated landslides is also visible. The cliff face was reinforced and scaled throughout its whole length.**

Stop 2

***Crocifisso del tufo* Etruscan necropolis. Participants will have first an overall view of the well-preserved necropolis with the “dice” tombs, typical of this area of the Etruscan region. The necropolis is located at the foot of the north-western part of the hill onto a wide terrace overlooked by a 45-meter high cliff. All tombs, forming a well ordered mosaic, were backward tilted by a rotational movement. Cracks are visible on many tuff blocks forming the tombs, likely as a consequence of the stresses induced by the movements. In a borehole drilled in 1978 into the terrace, more than 30 meters of tuff were found below the ground surface, thus indicating that the terrace had been produced by a large slump involving the margin of the tuff slab and the underlying clay (Manfredini et al. 1980). This failure probably occurred before the construction of the necropolis, which originally should be already located below the cliff (a similar necropolis was discovered on the southern clay slope). Tilting of the tombs was likely produced by a further rotation of the failed block.**

Stop 3

Underground cavity at the edge of the southern cliff (between the Cathedral and the San Francesco Church). The cavity was completely excavated in the pozzolanic facies of the pyroclastic formation, in particular within the uppermost softer layer. The cavity, formed by an irregular network of chambers and pillars, was excavated and used for different purposes. In ancient times the outermost chambers were used for pigeon keeping (*culumbarium*). Successively inner chambers were used for milling, storage of liquids and eventually for the exploitation of pozzolana, a fundamental ingredient for mortars. This activity was protracted until the first years of the 20th century. Within the programme for the preservation of the Orvieto cliff, most of the chambers forming the network have been restored and reinforced (especially pillars of the quarried area and outermost chambers, involved in the cliff instability).

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Civita di Bagnoregio

Civita di Bagnoregio, a medieval town whose origin dates back to Etruscans (7th c. BC), is located on top of a cliff at 443m asl (**Fig. 11**). The town was for centuries subject to landslides phenomena that have resulted in a progressive retrogression of the slopes and today jeopardize the very existence of the town, so that Civita is widely known as the "dying town". In recent decades, Civita has been affected by new and severe occurrences of landslides, focusing the attention of the town's administrators and the wider scientific community on the problem of safeguarding the town's existence, both with respect to civil defence and the conservation of its environmental and architectural heritage.

Fig. 11 - Panoramic view of Civita di Bagnoregio

Geological setting

Civita di Bagnoregio's cliff, surrounded by two river gorges lying roughly in an E-W direction, is made of pyroclastic rock deposits formed by the Vulsino complex of volcanoes, whose eruption activities took place between 880,000 and 40,000 B. P. (Nappi *et al.*, 1986, 1991). The pyroclastic sequence is constituted by a superficial stratum of ash-flow, made of red tuff containing black scoriae strongly compacted (massive tuff) with a depth of approximately 20–25m. This deposit presents cracks, sometimes open, oriented following two main sets. The two sets are fairly scattered, with prevailing directions of 50 to 80° N and 130 to 150°N, and a closer spacing near the edges.

Below this stratum is an air-fall ash deposit (stratified tuff) with a depth of approximately 40 to 50m made of several levels of pumice scoriae and cinerite (vitric tuff) with different geomechanical characteristics in relation to their position. Also in this case, we can observe a cracking pattern oriented in the prevailing directions of 50 to 70 degrees North and 150 to 170 degrees North, with an azimuth dispersion and open fault much lower than those of the massive tuff formation found in the higher stratum.

These volcanic materials stand above the Plio-pleistocenic clayey-sandy deposits below, having a depth of several hundred meters and a geotechnical character typically found in clays that are strongly over consolidated and fractured. At the top of the clayey formation a sandy-conglomerate discontinuous layer, of several meters thick, outcrops (**Fig. 12**).

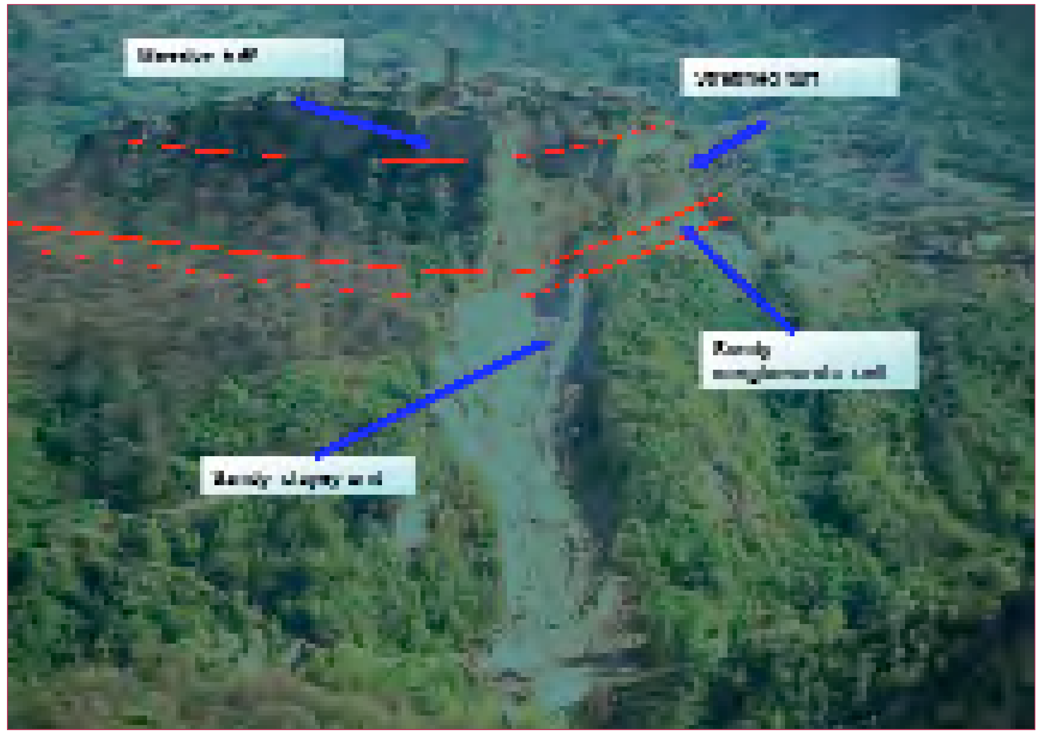

Fig. 12 - Stratigraphical sequence of Civita di Bagnoregio hill

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Reconstruction of historical landslides

The present morphology of the cliff of Civita is the result of events that have taken place over centuries. The chronology has been reconstructed through detailed scientific research into the available historical documentation (Margottini, 1990; Focardi, 1992; Baffo *et al.*, 1998; Delmonaco *et al.*, 2004). This analysis made it possible to reconstruct the events that led to the present configuration of the town and understand their origin (**Fig. 13**).

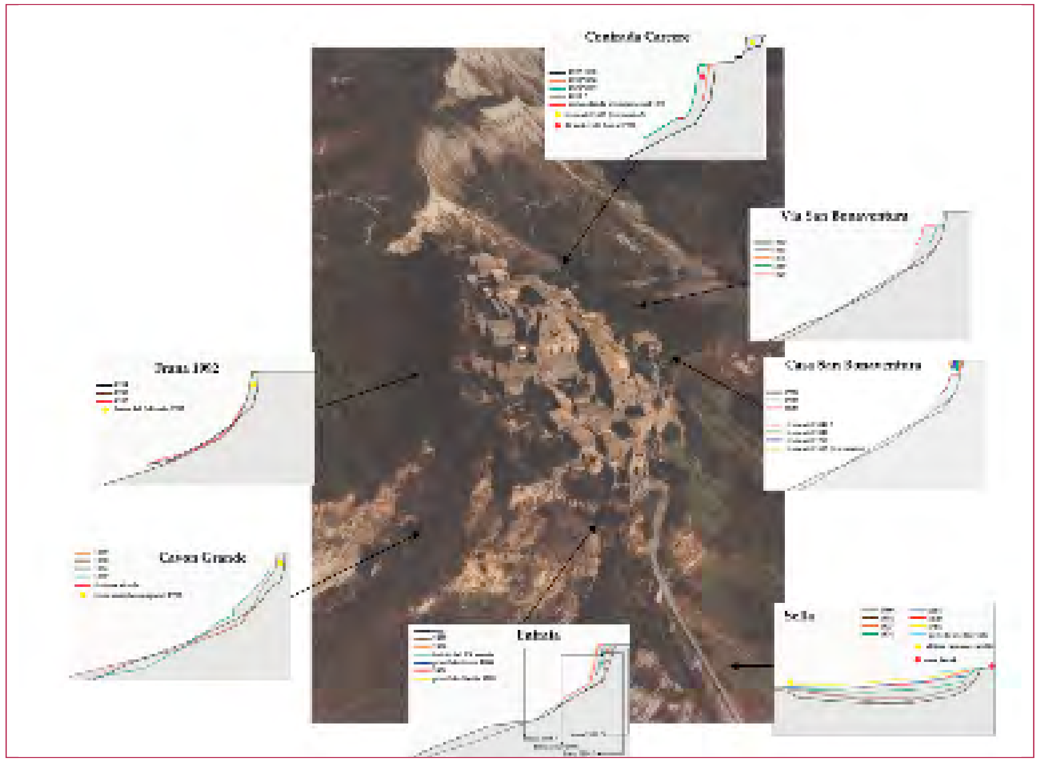

Fig. 13 - Landslide historical evolution of the cliff

The origin of the first settlement goes back to the Etruscan period or perhaps even earlier. The town went through periods of considerable expansion throughout the Roman and Medieval periods, and during the early Middle Ages, the quarters (*contrade*) of Ponte (west side toward Bagnoregio) and Carcere (east side toward the Tiber) were added to the nucleus of the town, determining Civita's supremacy over Bagnoregio, which was reduced to a simple suburb. These *contrade* then disappeared in the subsequent period. The decline of Civita began at the end of the Middle Age as a result of the progressive reduction in the town's surface area due to landslides and earthquakes. The first record of these occurrences can be dated to

1450, when the convent of the *Clarisse*, located in the *contrada* Carcere, began to collapse following a series of landslides. Then, between 1466 and 1469, a number of houses located on the north side of the cliff fell down, just in front of the hamlet of Lubriano. Similar events took place between 1554 and 1888.
The oldest information available regarding the connection between Civita and Bagnoregio can be dated to 1545, when it was necessary to modify the course of the road following a landslide of considerable proportions. A few years later, the Civita gate was destroyed, as was a section of the walls of the *contrada* Carcere, which in turn determined the destruction of a number of adjacent buildings.
Starting in the XVII century, more detailed information becomes available on the natural destructions occurring in Civita, including the collapse of the access road (1606-1608) near the church of S. Vittoria, later completely destroyed, as well as the falling of various buildings on the south side of the town, near the house of S. Bonaventura. The access bridge into the town collapsed again in 1684. Then, on 11th June 1695, an earthquake equivalent to 9 to 10 degrees on the MCS, with an epicenter near the town, brought down the bridge and caused large ground cracking throughout the residential area. The entire *contrada* Carcere disappeared in a ruinous landslide. This disaster determined the definitive decline of Civita: the bishop's residence was transferred to nearby Bagnoregio.
Among the numerous natural events occurring during the XVIII century, that of 1707 determined, in the aftermath of a major landslide, the obstruction of the stream Torbido. The bridge collapsed again in 1764 together with part of the convent of S. Francesco, later demolished to build the new road connecting Civita to the neighboring areas. In 1810, after various interruptions of the access road and the collapse of part of the cliff near the church of S. Bonaventura, various neighboring buildings were completely abandoned. In the XIX century, the church of S. Bonaventura collapsed, while that one of S. Vittoria was demolished after its partial destruction in 1888.
During the XX century, various landslides brought about the collapse of the road connecting Civita with the village of Mercatello. In addition to the usual natural disasters, 1944 saw events of a different nature cause as the destruction of the masonry bridge, by retreating German troops. The construction of a new wooden footbridge re-connected the town, which however was seriously damaged in 1963 with the collapse of part of the walkway and retaining wall. The present bridge was inaugurated in 1965.
Today, structural problems related to the bridge are limited to the foot of some of the piers, due to surface erosion, which may undermine their stability in the long term. *Figure 13* illustrates the distribution of documented landslides over the past six centuries. An increase in the number of natural disasters can be observed from 1550 to 1850, during the period of generalized climatic deterioration called the

"Little Ice age", which developed also as a result of the intense deforestation of the area from the XVII century. Also, during the past century (even if we take into account the increase in the sources of information and the higher level of public awareness regarding natural disasters), the frequency of these occurrences remained quite high, reaching an absolute maximum of nine events in the decade between 1950 and 1960.

Very important for the stability of Civita's slopes, especially on the north side, are the evolving phenomena along the side of the adjacent Lubriano. The greatest landslide event occurred in 1114, dated with radiometric techniques from vegetal remains found inside the body of the terrain (**Fig. 13**). This landslide effectively re-routed the Lubriano stream toward the north side of Civita di Bagnoregio and left the area much more unstable.

In recent years, a further series of landslides have occurred along the cliff and the slopes of Civita; among these we should mention a landslide in February 1992 in conjunction with an abundant snowfall, a rock-fall in August/September 1993 and a debris flow in December 1996, when the materials from the 1993 rock-fall, still present along the slopes, began again their downward slide. Finally, a small landslide occurred at the beginning of August 1998 near the access to the town, on the cliff below *casa* Janni. During the same period, we witnessed an acceleration of the stresses affecting the cliff on the northern side, with downfalls occurring in 1999 and 2001, and considerable debris flows in December 1994, which cut off the course of the stream Lubriano and jeopardized the outflow of water in the valley below the cliff.

Landslide types and evolution

Fig. 14 - Geomorphological evolution of the slope-cliff system

In the area of Civita di Bagnoregio the instability of the slopes can be explained by a complex and highly interdependent number of causes, which, beginning with the progressive deepening of the floor of the valley, affect the stability of the slopes and, eventually, that of the cliff above (**Fig. 14**). This ensemble of causes includes:

1. streams eroding downwards into their floors as a result of rainfall;
2. decay of the geotechnical characteristics of clay materials when exposed to the action of the atmosphere (loosening clay soil) up to a depth of 5–10m below the surface, with particular effects on the first 0.5–1m of depth;
3. mudslides occurring in the first 0.5–1m of soil depth as a result of intense rainfall, which determine a continuous removal of surface materials and exposure of new layers of soil;
4. intense surface erosion following the action of meteorological agents and rainfall (several cm per year);
5. deformation of base clay soils, loosened as a result of decay in their geotechnical composition and effects resulting from the subsidence of the upper strata of tuff rock;
6. initial fissuring at the base of stratified tuff formations as a result of the significant increase in eccentric stresses associated with the lack of lateral support at the edge of the slope;
7. increase in the deformation patterns occurring in the upper part of the cliff which, with the expansion of fissures in rocks with pre-existing cracks, spread inside the weaker formation of stratified tuff found in the lower levels of the cliff. In these strata, we observe a trend toward the development of tensile stresses, transformed into shear or rotational stresses when they meet the formation of plastic clay;
8. opening of pre-existing fissures in the higher strata of compact tuff as a result of thermoclastic and cryoclastic phenomena, as well as presence of water inside the cracks. The latter increases the interstitial pressure at the base of the lithotype. Occurrence of collapse at the top of the cliff, near the strata of compact tuff.

Finally, the presence of several cavities of anthropic origin, created inside the least cohesive portions of the stratified tuff and within the tuff rock, contributes an additional level of overall instability. The above-mentioned geological processes, which affect the cliff/slope/valley-floor system in the area of Civita di Bagnoregio, occur through the cyclical process shown in **Figure 14**, which at present affects principally the north side of the town.

The instability of the cliff starts with the structural deformation of the clay bedrock, determined by the erosion occurring along the valley floor and the medium-low levels of the slope (Phase 1). This process determines the evolution of fissures at the top of the cliff where the volcanic rocks appear on the surface, especially near the edge of the cliff (Phase 2), followed by a stage of pre-collapse of the tuff blocks.

This stage is followed by the occurrence of landslide collapses triggered principally by thermoclastic and cryoclastic phenomena (Phase 3). The collapsed blocks along the slope fall into the valley floor in the form of debris during the subsequent phase (Phase 4). This is the result of intense and/or lasting rainfall. After the conclusion of these phases, the side of the cliff goes back to the condition observed during Phase 1 (cliff deformation) in which the unprotected clay slopes begin to alter and transmit to the volcanic rocks above the tensile stresses active along the existing cracks.

Monitoring system, slope instability modelling and landslide hazard assessment

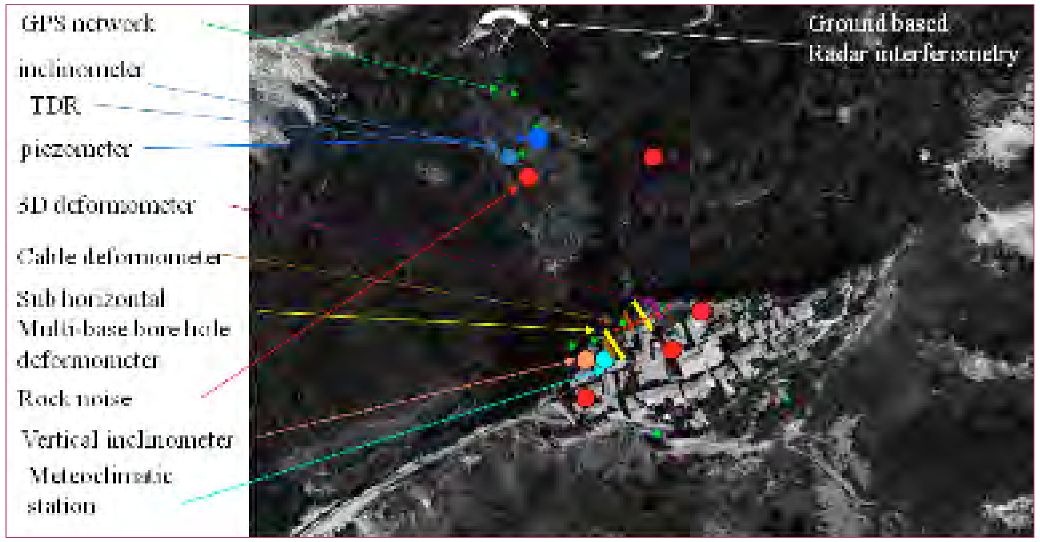

Fig. 15 - Monitoring network installed in Civita di Bagnoregio

A monitoring system was installed in March 2002 and mainly focused to the analysis of deformations in the northern cliff. The system includes: 1 inclinometer (equipped with TDR), 1 piezometer, 1 3D extensometer, 2 sub-horizontal multi base bore-hole extensometers, 3 cable extensometers, 1 crack gauge, 1 meteo-climatic station, GPS network, rock noise measurement and a ground based radar interferometer (**Fig. 15**). Slope stability conditions were also analysed with FLAC. Three main areas, displaying a critical safety factor, were analysed: the retrogressive area of Cavon Grande, affected by the large rock-slide of 1993; Casa Greco where the open failure is reducing the shear strength of the cliff and the lower part of the cliff where the deposition of tuff debris laying on the clay bedrock can generate debris flows. According to historical evidence of landslides and actual stability condition of the cliff a hazard map, based on landslide return period (Fell, 1984) was produced (**Fig. 16**).

Fig. 16 - Hazard map of the Civita di Bagnoregio top cliff. Return period is based on Fell (1984) classification (modified).

Consolidation works

Based on the above, a decision was made to stabilize the formation of compact tuff rock through the construction of cavity wells in reinforced concrete located near the landslide edge. This system makes it possible to secure the unstable tuff blocks near the exterior of the cliff with injections and tie-rods capable of transferring the eccentric loads to the stable mass of rock located inside the cliff. The tie-rods create a lateral anchoring system along the slope of the cliff and, above all, counteract the toppling, detachment or collapse of consistent portions of the tuff rock. This is realized by anchoring the outermost zone of the cliff, which is exposed to atmospheric and human-induced actions and has weaker mechanical properties, to the interior of the tuff rock, which is stronger. In addition, by virtue of their physical arrangement, the tie-rods make it possible to reduce the vertical loads exerted on the lower edge of the cliff near the stratified tuff, a type of rock with weaker mechanical properties.
The injections applied to the anchoring system guarantee the stability of the medium to small portions of rock, which, being prone to sliding, toppling and collapse, are naturally unstable (rock wedges); in addition, it improves the quality of the external rock formation, which is more exposed to deterioration, because of

the effect of cement binders filling the cracks along the slope. At the bottom of each cavity well, the insertion of micro-piles serves to absorb the vertical component of the stress triggered by the intervention. Following excavation of the wells, their lining and the insertion of the micro-piles, and once the relative movements have been checked to ensure the efficacy of the anchoring and uniformity of the materials, it will be possible to connect the various cavity-wells, thus establishing a unique and flexible structure. The main advantages of this innovative technique can be summarized as follows:

- the intervention is not carried out from the cliff, but from inside the highest part of the cliff; this solution improves safety conditions for the workers and avoids the installation of dangerous scaffolding anchored to slopes that are at risk of landslides;
- as the work is carried out from inside the cliff, there is no environmental impact resulting from the presence of scaffolding and service roads;
- there is a reduction in loads in the area facing the edge of the landslide, thus relieving the stress on the lower strata of rock;
- the new structural system, besides helping with the drainage of the soil, makes it possible to control the structural conditions during the excavation phase, as well as monitor the deformation of the parts of the cliff under stabilization, both during construction and in the subsequent phase, when the anchoring is tightened and put under stress.

The choice to realize cavity-wells leaves open the option of re-calibrating and tightening the anchoring, even long after the completion of the works. The wells will permit the creation of a series of semi-rigid structures inside the tuff rock, establishing a structural mesh linking various horizontal planes, both perpendicularly (tie-rods and anchors inside and outside the cavity-wells) and parallel to the front of the landslide (connections between wells). The other important safety advantage is that the initial drilling is much safer as, in the case of the cavity-wells, the process involves the anchoring of the well first inside and then outside. In this way, in case of detachment of unstable blocks (triggered by shock waves or vibration created by the drilling equipment) the workers and equipment would not be involved or affected. Following the actions taken to secure the side of the town at greater risk, namely the north side, it will be possible to intervene also in the middle of the cliff and on the floor of the valley, near the water streams. This will be done through interventions aimed at reducing the depth of the ravines and the consolidation, with in-depth drainage, and stabilization of the landslide masses, with reinforced slabs in the middle sectors of the cliff where the tuff rocks lie against the sand layers and the sand layers against the clay soils. The design of the

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project is the result of an understanding of the evolutionary mechanisms of cliff movement identified by the geological and technical studies carried out over the past twenty years (**Fig. 17**).

Fig. 17 - Low visual impact interventions and 3D-rendering of the mitigation works (upper left)

Stop 1. Lubriano.

From the town of Lubriano a spectacular front-view of Civita di Bagnoregio's norther side will help to analyse the main geological and geomorphological characteristics of the area. The area of the large landslide of 1114 occurred in the southern side of Lubriano, that caused triggering and acceleration of slope instability process in Civita, can be also observed.

Stop 2. Bagnoregio, the bridge.

The bridge is the only way of access from Bagnoregio to Civita. Before its construction, in 1965, the two towns were connected by a narrow path founded on the clayey slopes that have experienced in the past frequent landslides and progressive erosion. From the bridge it is possible to analyse the stratigraphical sequence of terrains, from the Plio-Pleistocene clayey bedrock to stratified and massive tuffs on the top.

Stop 3. South side

From the town's entrance, we will visit the south side that was mainly affected by landslide phenomena from the end of 16th century to the beginning of 19th century. This area was particularly damaged during the large earthquake of 1695. Some relevant monuments were disrupted due to mass movements and that seismic event such as St. Bonaventura's House and the Convent of St. Francis.
At the SE side the area of *Calanchi* (badlands) is visible, whereas, at the end of the road to Contrada Carcere an old Etruscan tunnel carved in the stratified tuffs connects the north and south slopes of the town.

Stop 4. North side

The north slope is presently the most hazardous portion of the cliff. Partially or totally damaged structures (*Casa Greco*) affected by rock-falls occurred in the last decade are still visible. Consolidation works (reinforced wells) will be visited and construction techniques discussed during the final part of the field trip.

THE SECOND WORLD LANDSLIDE FORUM

ANCONA

Ancona was founded by Greek settlers in the 4th century BC and is the capital city of Marche Region (Central Italy); it is located along the Adriatic Sea shore in coincidence of the northern slope of the promontory of Mt. Conero, a typical landmark of this section of the Adriatic coast; it is an important ad active seaport.

Fig. 18 – Aerial view of the Great Landslide (1982) of Ancona towards the seafront

On December 13th 1982, a large and deep landslide (the Great Landslide of Ancona city) reactivated along a slope located westward of downtown (**Fig. 18**), interrupting the State road "Flaminia" and the national railway ad damaging many buildings (AA.VV., 1986; Cotecchia, 1997). In the late '90s a preliminary plan for designing remedial measures and consolidation of the landslide started, but it was concluded that consolidation was difficult to be afforded, both due to very large expenses and to a very significant environmental impact. It was then decided "to live with the landslide", reducing nevertheless the risk for people living there. This was achieved through the realization of drainage systems (both deep and superficial) and the set up of an Early Warning System linked to an Emergency Plan managed by the Municipality of Ancona city: these are based on an integrated and

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continuous monitoring system at superficial and deep level of the whole area. Such project is the result of the best conjunction between human resources and a reliable technology in the early warning and monitoring field aimed at the safety of people living there.

The 1982 Ancona landslide

The western outskirts of the town of Ancona, a wide and hilly area that reaches a maximum elevation of 250 m a.s.l., has long been affected by slope instabilities. The last and most significant occurred in 1982 and still remains one of the most remarkable examples in Italy of deep seated mass movements in stiff clays. The landslide took place on Montagnolo Hill at 10:40 pm on December 12th, covering a 3.4 km^2 area from 170 m asl to the sea along a coastal front of about 1.7 km. The landslide lasted some hours; at the end of the event, in the morning of December 13th, the recorded displacements were: at the toe of the landslide, 8 m as maximum horizontal component and 3 m on height, while at the top 5 m and 2.5 m were respectively recorded downhill. The landslide damaged 200 private houses, interrupted the national railway and the State road "Flaminia" (Fig. 19 - picture of road statale Flaminia) because of line and level dislocations in the order of some meters; also two hospitals and the new Faculty of Medicine complex at Ancona University were seriously damaged. About 3000 people were temporally evacuated and 1562 of them were moved to hotels and other residences by Municipality and remained in such situation fore a long time.

Fig. 19 – An image of the landslide toe soon after the 1982 event.

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Site description: morphological and geological features

The northern slope of Montagnolo Hill has an average inclination of about 10° and a pre-slide topography characterized by peculiar morphological features. The wide extension and alignment of such features throughout the area show that they are the result of geomorphological evolution of the slope, mostly related to deep-seated, ancient, slope deformations. The morphological setting is characterized by slopes with an average inclination around 15-20° alternating with flat and broad terraces which are parallel to each other and to the coast. They extend for several hundreds meters, within and beyond the limits of the landslide area. The upper terrace shows changes in elevation probably due to ancient landsliding, while on the lower and larger one (Posatora) urbanization took place from the beginning of 20th century. The lower section of the hill, from Posatora terrace to the seashore, is featured by the steepest slope and shows the most remarkable morphological evidences of shallow and deep movements, such as circular scarps, a chaotic topography with evident bulged areas and diverted surface drainage (Fig. 20 - landslide map).

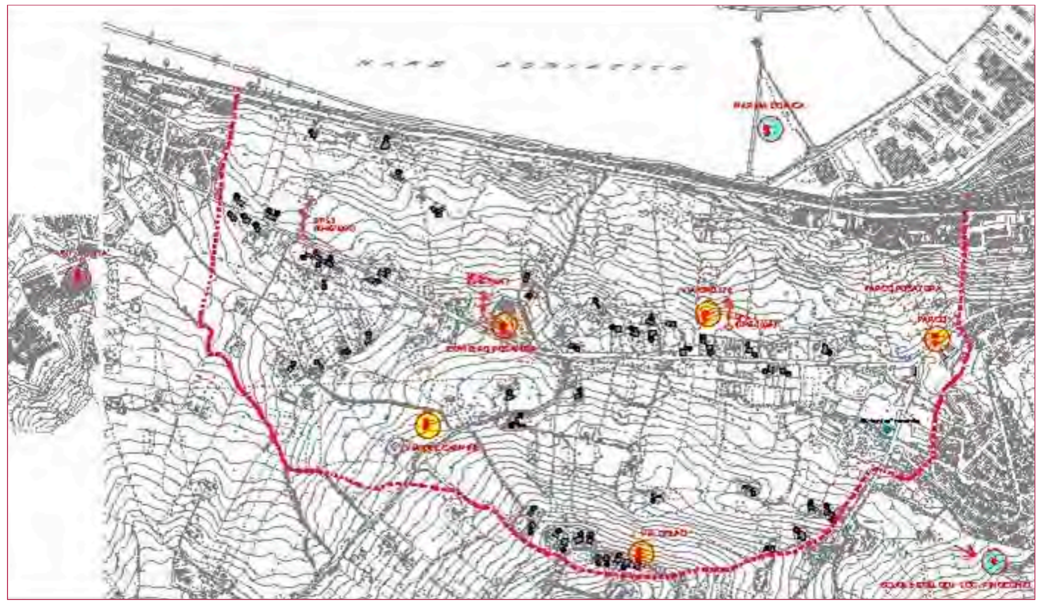

Fig. 20 - Map of the landslide and location of the stops

The Ancona landslide developed in Pliocene and Pleistocene sediments of marine origin. From the bottom to the top, the stratigraphic sequence consists of:
- Middle and Lower Pliocene grey-blue clays with grey and grey-yellow sand levels, increasing in frequency and thickness in the lower part of the series;
- Pleistocene sediments, which are grey-blue silty-clays and marly clays with sandy interbeddings in the upper part; the Pleistocene sediments are transgressive over Pliocene ones as a result of an important erosional phase;
- the Pliocene and Pleistocene sediments are covered by up to 10 m of eluvial and colluvial soils and by weathered debris material which were disarranged by ancient slope movements.

A significant tectonic activity had affected this section of the Apennines during Plio-Pleistocene age, inducing faults and folds (Bally et al., 1988; Cello & Coppola, 1989) and then a final, generalized uplift of the area.
The Ancona landslide can be framed in a regional context characterized by numerous deep seated (sliding surface at least 100 m deep) translational-rotational slides which formed from the top of the hill (mainly characterized by the outcrop of Pleistocene regressive sequences made of sandy-gravel horizons) to the sea shore and which frequently caused the upheaval of the sea bottom offshore the coastline (Cancelli et al., 1984). All of these deep seated landslides occurred during the rainy season and most of them were associated with shallow slips of the colluvial covers.

Historical hints

Slope instabilities along Montagnolo hill were not a singular episode but rather the dominant slope-forming processes, as historical records and technical reports describe several and frequent problems in this area. In 1858 a large landslide occurred along a 3 km long coast front. In 1919 two landslides took place at the same time, one in the upper part of the slope and one in the lower part (the Barducci slide). It was then suggested that the two slides might be connected through a single, deep sliding surface. The Barducci slide has been intermittently active in connection with rainfall and had caused cumulative damage to buildings, roads and services. Prior to the 1858 events, many historical records and reports describe a general situation of slope instability conditions, mostly related to road problems or coastal protection.
Besides the natural ad physical processes, human activities have had important effects on the slope evolution; for instance, clay quarries have been exploited at the toe of the slope along the whole coast, during the last two centuries. Such activity produced cuts and reshaping of the lower part of the slope; remnants of the old quarries are still present at Palombella borough. Urbanization gradually developed from 1800 towards uphill and in the last century it extended in the above mentioned Posatora morphological terrace. This led to slope profile modification by excavating and cutting it, redirecting runoff through the paving of extensive areas and concentrating infiltration due to leakage from water mains or sewage systems.
Even though a M 4.7 earthquake occurred in Ancona in 1972, no landslide resulted reactivated in the area in that occasion, thus suggesting that slope movements are not directly related to seismic activity. However, it cannot be excluded that seismic activity may have affected the deformational behaviour of the entire slope.

Studies and investigations before the 1982 landslide

During the 20 years preceding the 1982 landslide, many studies were performed in the area in order to assess the slope stability conditions, but all of them underestimated the dimensions of the potential landslide. The stability conditions of Montagnolo hill were not fully understood, as the previous studies focused on the lower part of the slope where shallow instabilities (like the Barducci slide) continued to damage houses and roads along the coastline. The first site investigations were carried out in 1963 with boreholes drilled to a depth of 30 m. In 1971 a technical report described instability phenomena affecting soil depths of about 4-8 m, and in 1977 the first levelling points were installed.

Studies and investigations after the 1982 landslide

Since 1982 many investigations and surveys were planned and carried out, including three main geotechnical investigations (Cotecchia et al., 1995; ITALGEO, 1987). More than 60 boreholes were drilled to a maximum depth of 170 m, recovering a large number of undisturbed samples; some boreholes were instrumented with piezometers and inclinometers to monitor groundwater level and subsurface displacements. Refraction, down-hole seismic and electrical sounding survey were carried out in 1983 (AA.VV., 1986). Topographic and photogrammetric studies helped in defining surface planimetric and altimetric displacements and since 1983 the displacement field was measured by precision levelling. Geotechnical and geophysical investigations were performed off-shore the landslide area, showing no significant deformation of the sea floor due to the 1982 landslide (Cotecchia et al., 1995). All the collected data allowed the formulation of a sound landslide model in order to plan mitigation measures, including stabilization works.

Landslide model

Geological setting

The structural setting of the landslide area had already been studied in previous investigations; however, different interpretations were proposed regarding the number, type, throw of the local faults as well as the bedding orientations, due to the complex geological setting of the area (Santaloia et al., 2004).
A detailed study was aimed at distinguishing the structural features caused by tectonic activity from those which resulted from mass movements affecting the slope over time. Such study was performed by making use of aerial photos taken before and after the 1982 event, ranging from 1943 to 1991. The oldest air photos allowed to identify and locate morphological features ad even minor structural discontinuities, before human activities modified the natural setting of the slope.
Four main fault systems were identified in the landslide area; *a)* a near vertical, NE-SW trending system almost transverse to the coast, *b)* a transverse-to-coastline system which shows a 45° dip direction; *c)* a sub-parallel-to-coastline system with a 0°-5° dip direction; *d)* a sub-parallel-to-coastline system with a 20° dip direction.
The structural discontinuities have had an important influence on the evolution of the slope, as they have produced distinct slope sections which are characterised by a different evolution and activity over time. The lowermost portion of the slope is featured by the most evident signs of instability phenomena, such as slip scars, soil bulges, hummocky morphology and disarranged topography. It is also evident from aerial photos and field investigations that the mechanism of the 1982 landslide is significantly influenced by structural discontinuities. In particular, there appears to be a correspondence between the fault system a) and the transversal scarps in the western part of the slide area, close to the Grottine cemetery. Fault systems c and d are correlated with scarps, trenches and fractures parallel to the coast which affected the area in 1982. In addition, geognostic investigation, field surveys and geophysical studies helped to identify a SSE-NNW-trending syncline in the landslide area. Changes in the dip direction of the strata (from a seaward to an inland direction) within the slope are related to this syncline.

Geotechnical characters

Based on site and laboratory investigations, three main geotechnical units have been defined (AA.VV., 1986):

- Unit *A* consists of colluvial soils and debris materials (mainly clayey and sandy silt with weathered sandy layers) as well as Plio-Pleistocene soils consisting of silty ad marly clays with interbedded fine sands.
- Unit *B* consists of Plio-Pleistocene silty and marly clays with interbedded sand layers, with variable dip ranging from 20-25° to 0-5°. Moisture content varies between 25 and 30%. The thickness of this unit is variable along the slope, reaching the maximum (60-70m) in the Posatora terrace.
- Unit *C* consists of Pliocene grey-blue clays ad thin interbedded sand layers. The strata are sub-horizontal; the moisture content is close to the plastic limit.

The transition from units *A* and *B* to the intact unit *C* is marked by a sudden increase in the seismic velocity, which is about 2 km/s. Unit *B* marly-clays are of medium to high plasticity and medium activity (A = 0.7 - 0.9). The unit *C* (Pliocene clays) is composed of heavily overconsolidated blue clays, as the preconsolidation pressure for samples at a depth of 110 m is around 9 MPa. The mechanical parameters are highly variable due to the presence of discontinuities, fractured zones and fissures caused by past slides and tectonic activity.
Shear strength parameters c' and ϕ' range respectively between 20-180 kPa and 21-28°, while the residual friction ϕ'_r angle is between 8.5 and 11°.

Groundwater conditions

During the period 1978-1982 the average rainfall amount was 820 mm/y with a maximum in November (88.4 mm) and a minimum in July (43.8 mm). In 1982 the rainfall reached a value of 931 mm, 50% of which during the three months preceding the event and 180 mm in December. A study performed by Cotecchia & Simeone (1996) on cumulative rainfall for the 100 years preceding 1982 shows that the rainfall amount associated with the 1982 landslide has a return period of less than 10 years, while the rainfall associated with the 1919 landslides has a return period longer than 100 years. Due to the lithological characters of the outcropping units and their structural setting, the permeability is heterogeneous and anisotropic, with the maximum permeability orientation coincident with the strata dip direction. Structural discontinuities, like faults joints and fractures play a crucial role with regards to storage capacity and preferential flow-paths. Such complex groundwater conditions are also indicated by piezometric measurements which show a regime featured by pressure heads decreasing with depth in the upper and central part of the slope (i.e. downward gradients) and piezometric levels increasing with depth and close to the ground surface in the lower section of the slope. Piezometric variations over time are negligible for the deepest piezometers, while are significant for the shallowest ones (installed between 25-40 m b.g.l.). Two distinct hydrogeological domains may thus be recognized: the first one is shallow and directly affected by rainfall, the second is deeper and not affected by rainfall.

The mode of failure and mechanism of the 1982 Great Landslide

The pattern of planimetric displacements measured in December 1982 showed two different blocks of the landslide mass which had different characteristics and behaviour during the landslide event. A predominant NNE direction of the displacement was evident in the central part of the landslide area, whereas a NW direction was recorded in the western part between Grottine and Torrette. By overlapping the displacement field and the structural discontinuities, it comes out that the landslide body is actually partitioned in two blocks as a consequence of the fault pattern. The location and the geometry of the sliding surface have been defined on the basis of geotechnical, geophysical and field data, including inclinometer measurements. The recent slope deformations do not seem to be controlled by a unique sliding surface, but rather by multiple shear surfaces along which the deformation occurs at various rates. Slip surfaces at intermediate depths appear to be discontinuous, whereas a deep sliding surface is identified at the maximum depth of 75 m in coincidence with the Posatora terrace. All the aforementioned observations confirmed that the 1982 landslide cannot be considered as a single block and that the structural discontinuities played a significant role in controlling the mode of failure.

Taking into account all the observed evidences and measured records, the lower section of the slope appears to be naturally at limit equilibrium conditions which were worsened by significant rainfall in 1982. For these reasons, the trigger for the 1982 landslide is supposed to be the collapse of the lower part of the slope along a surface located at medium depth. The displacement of this part represented a remarkable removal of lateral support for the entire slope which, in turn, contributed to the retrogressive sliding of the rest of the slope along a deep seated sliding surface; it is then possible to conclude that the Great Landslide of Ancona is a deep seated roto-translational slide.

In fact, field observations and measured ground displacements and deformations strongly suggest such mechanism of failure. Downward displacements have been predominant in the central part of the slope while upward displacements are localised at the toe of the slope, along the seashore between Borghetto and Palombella. The lower part of the slope was slightly compressed and bulged in comparison with the settlements occurred in the upper part of the slope, thus indicating that the movement started from the toe and developed at a higher velocity. The morphological terraces underwent extension and widening with the opening of cracks; this implies a prevailingly translational component of the movement along a planar surface under the majority of the slope. Such interpretation is supported by the fact that the first warning of the landslide came from the borough of Borghetto, near the coastline.

MONITORING SYSTEM

A preliminary design aimed at slope consolidation was produced in 2000, but it was suddenly considered to be particularly difficult both due to very large expenses ad to a significant environmental impact. As a consequence, the Ancona Municipality Administration decided to live with the landslide reducing the risk for people living there (Cardellini & Osimani, 2008). In 2002 the Regione Marche decided to give the Ancona Municipality the responsibility of creating an Early Warning Centre (EWC) and an Emergency Plan for the inhabitants. The EWC consists in an integrated and continuous monitoring at a superficial and deep level of the whole landslide area (**Fig. 21**). The first phase of the monitoring system, concerning the control of surface movements, has been operating for some months (I phase). In 2009 the Geotechnical in Place Continuous Monitoring System (II phase) was also activated.

Fig. 21 – View of a total station within the landslide

Surface Monitoring

The surface monitoring system consists of:
- 8 Automatic Robotic Stations (ARS) of high precision
- 230 reflector points (installed partly on 64 inhabited houses ad on other structures and infrastructures)
- 26 geodetic GPS at single frequency L1 (installed on the mentioned 64 houses)
- 8 geodetic GPS at dual frequency L1+L2 (reference)
- 24 high precision Clinometric Sensors (CS) for the stability control of the main stations of the I and II level of the net (automatic geodetic boxes).

The combination of the different instruments (GPS, ARS and CS) allows a 3D monitoring of a great number of points previously identified, from different control positions. The adoption of the geodetic GPS at dual frequency assures a high quality of the GPS measurements and a greater versatility to the entire system. Such monitoring system has been designed to determine every surface movement both in the landslide area and in the houses and to produce an alarm managed by an Early Warning Centre H24 located in the Town Hall building, where a specific technical staff is operating. Whenever the situation is considered as critical, the coordinator starts the Civil Protection Plan. The measuring cycle is usually set up every 30 minutes, but in emergency or after a long rainy period, the system can operate on each point of the dual frequency GPS net also in Real Time RTK, and with the 8 Automatic Robotic Stations (ARS).
The surface monitoring works on a GPS system in 3 different active levels, on 8 ARS and a later control through the 24 high precision CS for the stability control of the main stations of level I and II of the monitoring network.

A - GPS system:
1. Main Network (I level) formed by 3 main stations outside the landslide area with 3 geodetic GPS at dual frequency L1+L2 (reference) placed on two steady buildings and a third one placed on a geodetic box at Marina Dorica (in the seaport) founded on a reinforced concrete pole (18 m) and 5 stations inside the landslide.
2. Secondary Network (II level) formed by 5 main stations inside the landslide area with 5 geodetic GPS at dual frequency L1+L2 (reference) placed on a building and on 4 geodetic boxes founded on reinforced concrete poles (12-18 m). All these geodetic GPS form a high precision net working in the Early Warning Centre, on different control levels, to assure the GPS net (at a single frequency L1) installed on 26 inhabited houses, the capacity to work in RTK after any alarm.
3. Third Network (III level) formed by 26 geodetic GPS at single frequency L1 installed on 26 inhabited houses inside the landslide area.

B - Automatic Robotic Stations (ARS)
The 8 high precision ARS are placed in the I and II level networks, in the same places of the geodetic GPS at dual frequency L1+L2, except for the "Collodi School" building. They control angles and distances of 230 reflector spots placed on the remaining inhabited houses and the remedial structures built inside the landslide area.

Geotechnical Monitoring

A geotechnical monitoring system DMS is also currently operating (patents and trade mark CSG-Italy); it is made of 3 boreholes (100 m), all instrumented with a Dynamic Modular System column (**Fig. 22**).

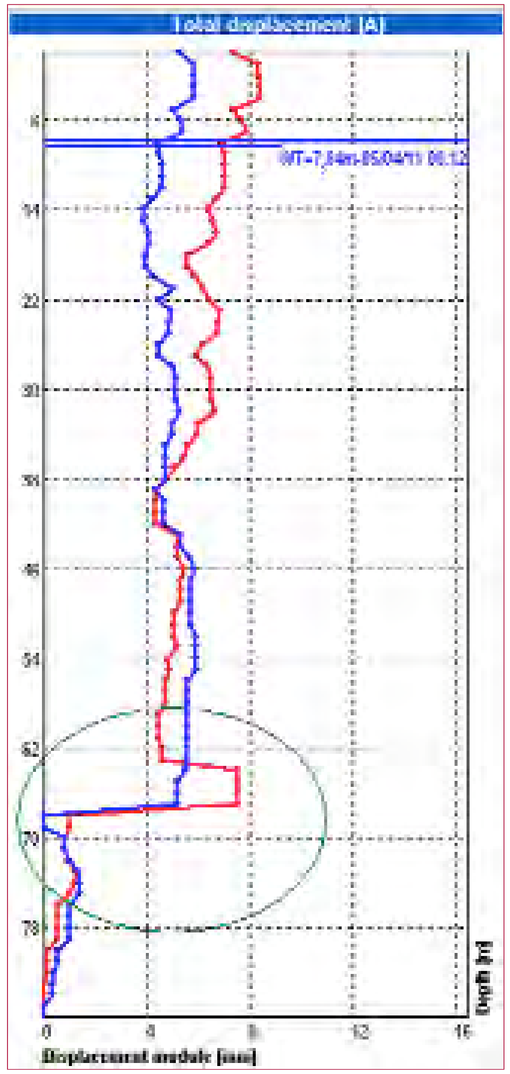

Fig. 22 – Plots of displacement measurements recorded through the DMS

Each column is formed by 85 biaxial Inclinometric modules (range +/- 20°, resolution 0.01), 2 Piezometric sensors (range 200psi resolution 0.01), 85 temperature sensors (range 0-70°C, resolution 0.1) for a total active length of 85 m (excluding the first 10 m and the last 5 m). DMS has been preassembled and installed in site forming an instrumented column, like a spiral cord, connecting modules and electronic boards for data collection and transmission. The modules are linked by special 2D/3D flexible joints that allow strong, continuous adaptability to bends and twists of the boreholes, whilst rigorously maintaining the orientation with respect to a reference system defined during installation.

DMS Early Warning Management

The data from the DMS instrumentation columns are sent through RS485 protocol to the Control Unit which compares them with threshold values (set by the users) and storages them in a circular buffer. In case of movements larger than fixed threshold values, the control unit sends a warning SMS/direct call to the technical staff on duty at the Early Warning Centre H24 in the Town Hall building. The same action is taken in case of rapid changes of groundwater-table levels. Warning levels are from 1 to 4, in a growing order of danger. In the Early Warning Centre, the control software GeoMaster takes care of downloading the stored data in the control unit memory buffer. DMS Early Warning is the software that visualizes the subsurface data at the Early Warning Centre and wherever an Internet connection is possible. A contextual control of displacements, as well as the groundwater level and temperature is enhanced; time histories of each multiparametric module and displacement velocity are also displayed at selected intervals.

Transmission System

The transmitted data coming from the different sensors are collected according to the following procedures.

I and II Level Net: data transmission in real time through a WiFi Standard HyperLan to the Monitoring Control Centre H24. The system is based on a main radio line (spot to spot) between the ARS and the Monitoring Control Centre H24. Data transmission in real time works through free frequencies radio links of 5.4 GHz (HyperLan). It realizes a strong transmission and a low environmental impact thanks to their noise control system.

III Level Net: data transmission through periodic GSM in "dialing" with a data acquisition every 6 hours.

Fig. 23 – View of the landslide from Marina Dorica (Stop 1)

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Stop 1. Marina Dorica

From the port of Ancona it will be possible to have a spectacular front-view of the Great Landslide of Ancona (**Fig. 23**). The geological and geomorphological setting of the slope will be introduced as well as the geotechnical model of the great landslide. In this place it is also located one of the stations belonging to the Monitoring Network.

Stop 2. Landslide area (Posatora terrace)

This stop will be dedicated to the visit of a Monitoring box inside the landslide area; the main features of the surface and geotechnical monitoring systems will be presented and a close up view of the landslide will be offered (**Fig. 24**).

Stop 3. Town Hall building (Palazzo degli Anziani)

Within an ancient building (on the opposite side of the harbour) it is located the Early Warning Centre. After coffee-break, it will be possible to visit the heart of the Monitoring Network to appreciate the unique atmosphere given by a High Tech control/warning system located in a historical building. The visit will be guided by the Chief Manager of the Early Warning Centre.

Fig. 24 – View from stop 2 towards the port (Posatora area).

FIELD TRIP TO ORVIETO, CIVITA DI BAGNOREGIO AND ANCONA: AN ITINERARY THROUGH LANDSLIDES, CULTURAL HERITAGE AND INNOVATIVE SOLUTIONS FOR MONITORING
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