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DISPLACEMENTS ON A SLOPE AFFECTED BY DEEP-SEATED GRAVITATIONAL SLOPE DEFORMATION: GRECI SLOPE (LAGO, CALABRIA, ITALY)

ABSTRACT: BONCI L., CALCATERRA S., CESI C., GAMBINO P., GULLÀ G., NICEFORO D., MERLI K. & SORRISO-VALVO M., *Displacements on a slope affected by deep-seated gravitational slope deformation: Greci slope (Lago, Calabria, Italy)*. (IT ISSN 0391-9838, 2010).

The study zone extends over an area of ca. 3.5 km^2 in the Tyrrhenian Coastal Chain, northern Calabria, Italy. It includes an east-facing slope for all its length and the valley floor of the Licetto Torrent that drains to the Tyrrhenian sea. The complex Geology is made of different thrust nappes forming an allochtonous tectonic building piled up in Oligocene - Lower Miocene, upon which Quaternary alluvial and colluvial deposits lie. Deep-seated gravitational slope deformation of *Sackung* type affects the Greci slope (Lago, Calabria, Italy).

The study faces this complex phenomenon by means of geological, structural, geophysical, geomorphologic, geotechnical, historical and dendrochronological tools.

Monitoring of surficial and deep-seated displacements is one of the fundamental investigations. GPS measurements, performed since 1996, depict a complex scenario of displacement, consisting in different sectors moving at rates ranging from less than 0.2 cm/y to 10 cm/y. Measurement of deep-seated displacements have been performed along two inclinometric verticals both 100 m deep. At northern site displacements consist in an upper section 28 m deep moving at a steady rate of ca. 1 cm/y; at the southern site displacement rate is much larger, ca. 10 cm/y, and rather uniform, down to a depth of 60 m.

These results provide kinematic data regarding the present evolution of the phenomena, necessary for developing a geotechnical model of the unstable slope and, consequently, to define the most probable collapse scenario.

Key Words: Landslide monitoring, GPS, Inclinometer, Deep-seated gravitational slope deformation, Displacements, Calabria (Italy).

RIASSUNTO: BONCI L., CALCATERRA S., CESI C., GAMBINO P., GULLÀ G., NICEFORO D., MERLI K. & SORRISO-VALVO M., *Spostamenti in un versante affetto da deformazione gravitativa profonda di versante: il versante di Greci (Lago, Calabria, Italia)*. (IT ISSN 0391-9838, 2010).

Il versante di Greci, situato in prossimità dell'abitato di Lago (Calabria, Italia) nella Catena Costiera, con quote che variano tra i 300 e i 900 metri s.l.m., è interessato da un fenomeno di Deformazione Gravitativa Profonda, tipo Sakung, nel cui ambito si sovrappongono frane da superficiali a profonde.

La geologia dell'area di studio vede la presenza di differenti falde tettoniche mese in posto nell'Oligocene-Miocene inferiore, sulle quali poggiano i depositi alluvionali e colluviali quaternari. Il dominio alpino, derivante dalla crosta oceanica e continentale, è rappresentato da depositi metamorfici di basso grado mentre sedimenti carbonatici di piattaforma di età triassica costituiscono il dominio appenninico e affiorano in finestra tettonica alle estremità meridionale e settentrionale dell'area in studio.

Nella presente nota sono trattati in particolare gli aspetti relativi alla caratterizzazione cinematica del versante di Greci che, essendo interessato da una DGPV, la rende complessa e richiede misure per un periodo adeguato.

L'approccio seguito individua nel monitoraggio conoscitivo la prima fase di un percorso che ha tra i suoi obiettivi la realizzazione di una rete di monitoraggio integrata, utile anche per il controllo dell'efficacia degli interventi di stabilizzazione e per l'allerta rispetto all'attivazione di fasi parossistiche di movimento. Lo studio cinematico del versante di Greci ha visto, a partire dal 1996, lo sviluppo di ricerche per la progettazione e la realizzazione di reti di monitoraggio conoscitivo degli spostamenti profondi e superficiali in versanti interessati da fenomeni di instabilità complessi. L'attuale rete GPS presenta una configurazione che è il frutto di integrazioni avvenute nel tempo sulla base del progressivo approfondimento del quadro conoscitivo. Nel corso del monitoraggio la strategia di misura è stata rimodulata per ottimizzare i tempi di rilievo e per migliorare la precisione delle coordinate. La notevole quantità di dati acquisiti ha consentito di confrontare le elaborazioni condotte con software commerciali e scientifici e di verificarne l'affidabilità.

La rete GPS comprende due sottoreti costituite rispettivamente da 6 punti interni all'area in frana, misurati con metodologia statica, e da 16 capisaldi misurati in modalità statico rapida fino al 2002. La velocità media dello spostamento, cumulato su tutto il periodo di misura consente di

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classificare i capisaldi in tre gruppi con velocità media annua: minore di 0.50 cm/anno, tra 0.50 e 2.00 cm/anno, maggiore di 2.00 cm/anno.

La rete di monitoraggio degli spostamenti profondi è costituita da due verticali inclinometriche spinte sino a circa 100 m. In una verticale, misurata dal 1996, si rileva una velocità di 1.20 cm/anno; nella deformata si distinguono tre tratti. Lo spostamento si annulla a 90 m. Lungo la seconda verticale, misurata dal 2002 e interrotta nel 2003 dall'eccessiva deformazione dei tubi, la velocità rilevata è stata di circa 9 cm/anno.

I livelli piezometrici, misurati lungo alcune verticali localizzate in due delle tre zone identificate sulla base delle caratteristiche cinematiche, evidenziano oscillazioni da circa 0.10 m a circa 2.50 m.

Il monitoraggio conoscitivo degli spostamenti svolto nell'arco di circa dieci anni mostra un buon accordo tra le misure di superficie e profonde.

Gli elementi acquisiti indicano che il versante di Greci è sede di una DGPV, con spessori dell'ordine dei 100 m, che si muove con velocità dell'ordine dei 0.50 cm/anno. Nella stessa area sono state identificate frane mediamente profonde (zona Piscopie) e profonde (zona Acqua Fredda), caratterizzate da cinematismo prevalentemente traslazionale e, rispettivamente, da velocità (costanti nel volume instabile) dell'ordine di 1 cm/anno e di 10 cm/anno.

I risultati dello studio condotto definiscono in definitiva il comportamento cinematico di un versante interessato da una complessa condizione di instabilità e, nel contempo, consentono di programmare efficacemente gli ulteriori approfondimenti conoscitivi.

TERMINI CHIAVE: Monitoraggio frane, GPS, Inclinometri, Deformazione gravitativa profonda di versante, Spostamenti, Calabria (Italia).

INTRODUCTION

Some shallow and deep-seated slope instabilities have been detected on the Greci slope close to the village of Lago (Calabria, Italy). On this slope *low-grade* metamorphic rocks crop out (fig. 1).

On the Greci slope, Sorriso-Valvo & *alii* (1999) identified a deep-seated gravitational *slope* deformation and a number of ancillary landslides of different types, fig. 1.

Given the characteristics of the Greci slope, that are common to other geo-environmental contexts for several different aspects (Sorriso-Valvo, 1979; 1984; 1988a, b; Sorriso-Valvo & Tansi, 1996), it is very difficult to depict and validate a slope evolution model able to provide a unitary explanation of the different instability mechanisms that could be triggered. Therefore, in these contexts it is diffi-

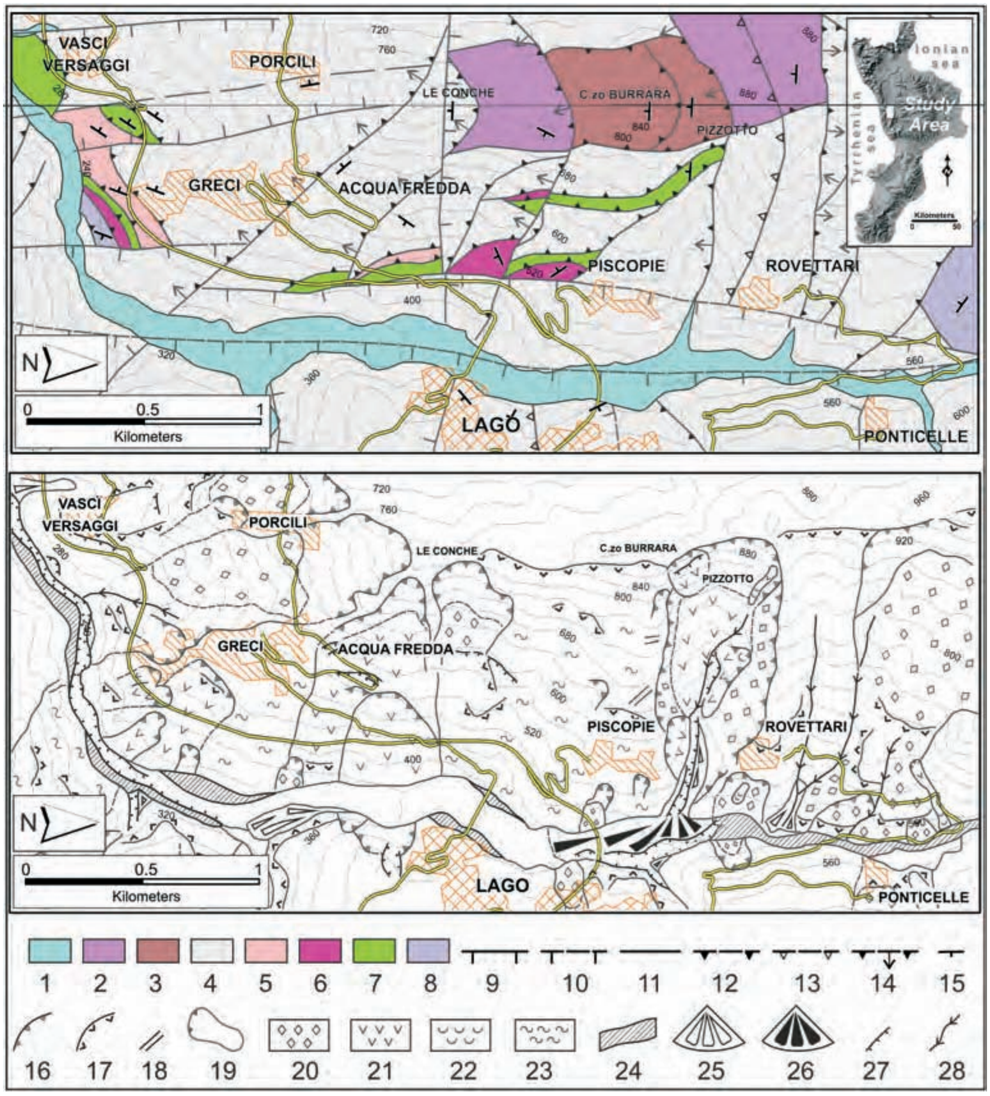

FIG. 1 - Lithological-structural and geomorphological sketch maps of the Greci slope (Lago, Calabria, Italy). LEGEND: 1) alluvial deposit; 2) porphyroid; 3) gneiss; 4) phyllite; 5) metabasite; 6) metacalcarenite; 7) quartzite; 8) carbonatic rocks; 9) normal fault with strike-slip component; 10) inferred normal fault with strike-slip component; 11) fault; 12) thrust fault, teeth on the upthrown block; 13) inferred thrust fault; 14) thrust fault with gravitational dip slip accommodation; 15) layering; 16) landslide main scarp; 17) sharp convexity or crest edge; 18) trench; 19) landslide body; 20) debris flow or earthflow debris; 21) rock or earth slide debris; 22) mudflow debris; 23) rock flow (*Sackung*); 24) 1951 river deposit; 25) inactive fan, channel fill; 26) active fan; 27) erosion scarp; 28) down-cutting stream (from SORRISO-VALVO & *alii*, 1999 modified).

cult to define geotechnical models able to simulate instability processes in their essential aspects, to forecast paroxysmal phases and to effectively define measures for landslide mitigation and risk reduction with the support of integrated monitoring networks.

For the reasons outlined above, an interdisciplinary research has been developed with the aim to define and validate an evolution model for the Greci slope, able to explain fundamental aspects of the complex relationships existing among the different types of instabilities detected on the slope (Sorriso-Valvo & *alii*, 1999; Gullà & Niceforo, 2003; Gullà & Antronico, 2004).

In this paper, after a summary of the results of the geological, structural and geomorphological analyses, the following will be outlined: the criteria considered for the design and implementation of the monitoring networks used for the kinematic characterisation of instabilities on the observed slope; the results of the measurements carried out over a significant time-span (1996-2006). These measurements have been analysed to highlight the elements that contribute to define the kinematics of the current instability phenomena.

GEOLOGICAL, STRUCTURAL AND GEOMORPHOLOGICAL FRAMEWORK

The area under investigation (fig. 1) extends for about 3.5 km^2 in the Tyrrhenian Coastal Chain, northern Calabria, Italy.

It includes an east-facing slope for all its length and the corresponding valley floor of the main course of the Licetto Torrent that drains to the Tyrrhenian sea. Elevation ranges from 300 to 900 m a.s.l.

The study area displays a complex geology made of different thrust nappes forming an allochtonous tectonic building piled up in the Oligocene-Lower Miocene (Ogniben, 1973), upon which Quaternary alluvial and colluvial deposits lie. Late thrusting occurred in Late Miocene (Messinian) and lower Quaternary (fig. 1).

The tectonic nappes belong to the Alpine and the Apennine palaeogeographic domains (Amodio-Morelli & *alii*, 1976). Nappes of the Alpine domain overly those of the Apennine domain, that crop out in tectonic windows in the northern and southern ends of the study zone. The terranes of the Apennine domain are represented by the sediments of the Triassic carbonate platform; those of the Alpine domain derive from the oceanic and continental crust, and they form several tectonic units.

Only one unit derived from the oceanic crust crops out. It consists of ophyiolite-bearing phyllites with quartzite veins and beds of meta-calcarenites and metabasites. It lies in a lower stratigraphic position with respect to those derived from the continental crust except for the southern end of the slope, where it overrides the terranes of the continental crust because of a thrust fault (fig. 1). The layering is intensively deformed by folding, faulting and jointing; its general attitude dips south, i.e. transverse with respect of the slope gradient that dips east.

Two units derive from the continental crust. One is made of porphyroid; the other is made of gneiss and white schist. Both units are intensively jointed and deeply weathered.

Alluvial and colluvial deposits are scattered all over the study area; at places, the thickness of alluvial beds may reach over 30 m, as in the Vallone Pizzotto fan. Colluvia can locally reach a thickness of 2 m.

Tectonic features make a rather intricate network which is the result of the deformation occurred during different tectonic phases occurred during the piling-up of the allochtonous nappes, but also before and after these events.

Tectonic deformation has eased weathering to depth, so that a thick superficial horizon of the bedrock is reduced to saprolite, especially on slopes where transport-limited processes dominate (Carson & Kirkby, 1972).

The geomorphology of the studied area (fig. 1) (Sorriso-Valvo & *alii*, 1999) is, at first glance, relatively simple, but it actually denotes its accommodation to tectonic features and lithological properties of the different tectonic units. This can be easily seen if the following is considered:

a) first of all, the valley floor of the Licetto Torrent is adapted to a major fault striking N-S and dipping east at a high angle;
b) main tributary canyons dissecting the study slope correspond to thrust ramps;
c) high-declivity scarps and cliffs consistently correspond to outcrops of harder rocks (especially metacalcarenites and quartzites) generally forming ramps along the thrust surfaces, including the main slope break that occurs at the upper 2/10th of the slope height;
d) slope gradient depends on the hardness of the different units;
e) mass movement involves almost all the slope, but while the phyllites play an active role, harder rocks of continental domain play a passive role as they in general accommodate to the deformations occurring in the phyllites underneath them. This can be seen in the Pizzotto canyon where collapsing phyllite entrains large blocks of gneiss.

The slope has an average slope angle of 25°, this depending on the neat prevalence of phyllites among outcropping terranes.

Mass-movement of different types and selective erosion are the main processes controlling the geomorphic evolution of the slope. In particular, a deep-seated gravitational slope deformation of *Sackung* type (Zishinsky, 1969; Varnes, 1978) affects almost the lower 8/10th of the slope (fig. 1). Rock slides (Varnes, 1978) affect the southern part of the slope, at and near the subdivision of Greci, while a landslide-fan system (Sorriso-Valvo, 1988a) develops along the northern boundary of the Sackung. Smaller slides are developing in the lowermost part of the slope and small falls and topples (Varnes, 1978) occur on the steepest cliffs.

Geomorphologic evidence of active mass-movement was quite clear long before the beginning of the study, especially as regards the Vallone Pizzotto landslide-fan system (Sorriso-Valvo, 1988a) and the Acqua Fredda landslide (fig. 1). The presence of the Piscopie-Greci Sackung was first supposed, on the basis of geomorphologic features, and subsequently confirmed by means of geophysical, geotechnical and dendrochronological investigations (Sorriso-Valvo & *alii*, 1999; Fantucci & Sorriso-Valvo, 1999; Ferrucci & *alii*, 2000).

Results of these studies were controversial, as it was apparent that major slope forms are due to selective erosion (due to difference in hardness of rocks), while evidence of widespread landsliding whic is normally associated with deep-seated gravitational slope deformation (Scheidegger, 1984), and of slow-motion displacements are widespread all over the slope; such evidence consists in the deformation and cracking of buildings and roads (Sorriso-Valvo & *alii*, 1999; Fantucci & Sorriso-Valvo, 1999). Subsequently, a geophysical study (Ferrucci & *alii*, 2000) confirmed the presence of a upper disturbed layer over 70 m thick.

In the Piscopie sector, there is no evidence of forms, such as scarps or slope hummocky morphology, that are normally diagnostic elements to detect landslides. It is thus evident that the slope is undergoing deep-seated rock creep; in other terms, it is a Sackung (Zishinsky, 1969), probably one of the very few cases of this phenomenon for which deformation is measured. The lack of evidence of shearing surfaces at ground surface indicates that there is not a continuous shearing surface, which is a typical feature of Sackung (Dramis & Sorriso-Valvo, 1994). This particular phenomenon is at an incipient stage, and it will probably form trenches and other typical forms of Sackung in the future, and could eventually transform into a large-scale rock avalanche (Goguel, 1978; Radbruch-Hall, 1978; Varnes, 1978; Sorriso-Valvo, 1988b, 1989).

A large earth slide affects the middle part of the study area. It is the Acqua Fredda landslide partially involving the Greci subdivision. This landslide extends over a surface of about 0.6 km^2, with a length of about 900 m and a maximum width of 650 m. It is an old landslide, with a wide main scarp and several secondary scarps some of which are newly formed because of the present movements (fig. 1). On the basis of cracks distribution on buildings and roads, the whole landslide results as active, moving in some places more than in others. It is not clear whether the foot of the landslide emerges from the slope above or below the present valley bottom. A secondary landslide, however, has moved onto the riverbeds, but its shearing surface seems not to be part of that of the main landslide. On the basis of the geometry of the moving mass the movement is a translational slide, even if the forms typical of translational slide, such as graben-like pattern of surficial fractures (Rib & Liang, 1978), are not evident yet.

Based on geomorphologic evidence, one can tentatively assess a thickness of 30-40 m.

Adjacent to the main scarp of the Acqua Fredda landslide, there is the main scarp of an another older and larger landslide about 1800 m long and 500 m wide, set along the right flank of the Sackung. This landslide is largely eroded and it seems inactive at present.

KINEMATICS OF THE PHENOMENON

Design and Implementation of the Monitoring Networks

The aim of the monitoring network is to define the kinematics of mass-movements, check the effectiveness of stabilisation actions and to operate as an alert system in case of paroxysmal movements. Such an aim requires a manifold monitoring activity. Starting from 1996, the study of the kinematics of the Greci slope has supported the design and subsequent implementation of monitoring networks for deep-seated and superficial phenomena (fig. 2). The first network was made up of inclinometric vertical tubes while the second is made up of GPS benchmarks integrated with topographic control points (Antronico & *alii*, 1999).

The logistic features of GPS network as well as the morphology of the area have been taken into consideration, both having an impact on the practicability of the site, the satellite visibility and, as a consequence, on the accuracy of obtained measurements. Therefore, the network has been designed so as to respect homogeneity in the baseline length and limit the vertical separation among the vertexes as much as possible (Bonci & *alii*, 2004).

The present configuration is the result of an iterative process which, on the basis of the results gradually acquired, has led to the reorganisation of the network as a result of the progressive integration and improvement between an initial network configuration (initial network) and a final configuration (present network).

The initial GPS network on the Greci slope had been originally developed and measured by the University of Calabria (Ferrucci, *personal communication*, 1996). It was made up of two different sections: a reference network with five stations (*R1*,…, *R5*), measured using the static mode, and a control network made up of 13 benchmarks (*L1*,...., *L13*), surveyed in fast-static mode and located on the Greci slope (fig. 2). In October 1996 the first GPS survey was carried out by the Italian Geological Survey.

The comparison between the data of the last survey carried out by the University of Calabria (February 1996) and the first survey carried out by the Italian Geological Survey (October 1996) enabled researchers to perform a preliminary evaluation of the movements in the area. Such initial comparison highlighted the presence of sectors characterised by different kinematics in Greci slope: the area of Acqua Fredda shows displacements of some cm/y, while the area of Piscopie showed rates lower than the errors of the measurement methodology (Antronico & *alii*, 1999). These initial indications oriented the further choices concerning the geometry of the GPS network.

Starting from 1997, the initial network has been progressively revised by introducing the new reference station (*R6*-fig. 3) and adding new tridimensional forced centering benchmarks to the already installed ones equipped with self-centering columns and a double system to check verticality, i.e. spherical bubbles and plumb wire to minimize planimetric and vertical errors of reoccupation (fig. 3, inset).

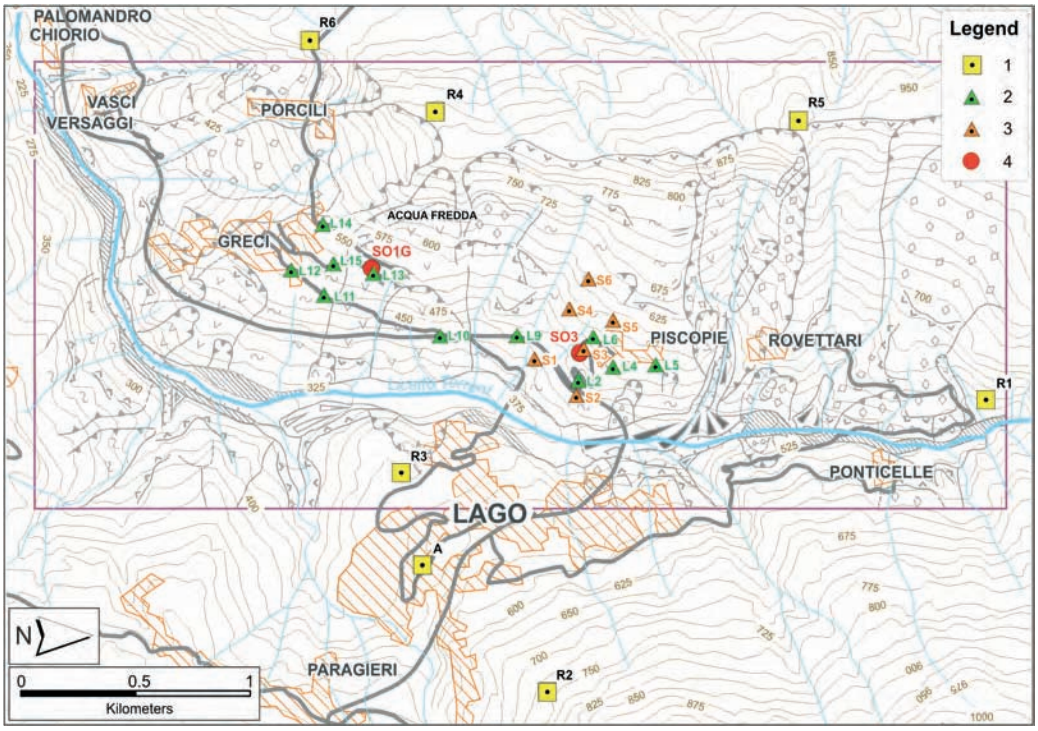

FIG. 2 - Monitoring networks for superficial and deep-seated displacements. LEGEND: 1) GPS reference point measured in static mode; 2) GPS control point initially measured in fast-static mode; 3) control point measured in static mode; 4) inclinometer vertical. The benchmarks *L1*, *L3*, *L7* and *L8* are not mapped because respectively coincident with *S2*, *S3*, *S5* and *S6*.

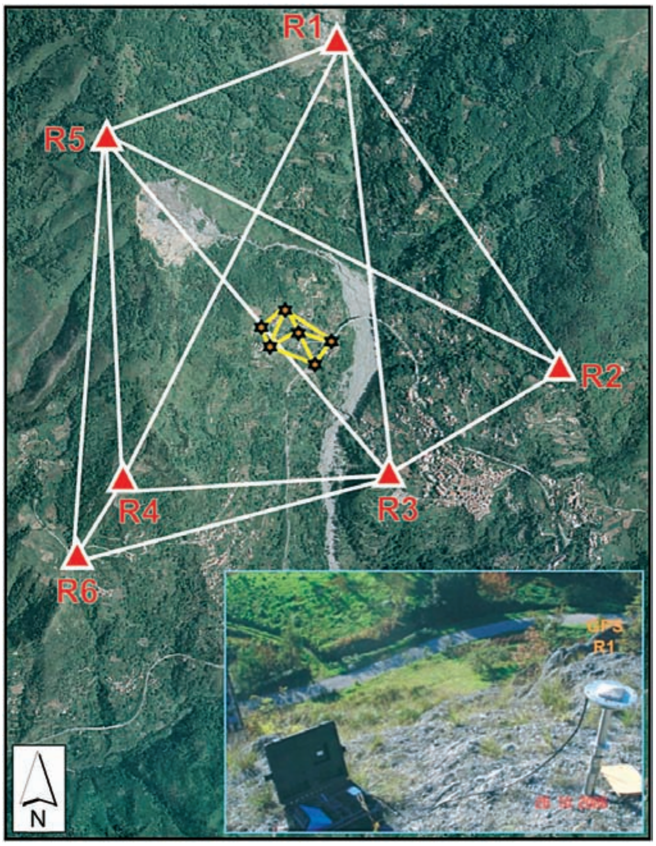

FIG. 3 - New GPS network: reference network (*R1…..R6*, triangles in the figure); static sub-network (*S1…..S6*, stars in the figure); inset: self-centering three-dimensional benchmark.

The measurement of the vertexes of the initial network went on up to 2002, before being abandoned.

In the sector of Piscopie, where the slowest movement had been detected, the initial network has been integrated with a control sub-network (*S1,…..S6*) measured in static mode so as to obtain better resolution of the displacements (fig. 3). In particular, a self-centering three-dimensional benchmark (*S3*) was located at the top of the inclinometric tube SO3 (fig. 2).

Three-dimensional benchmarks have been employed also in the implementation of new control points (*L14*, *L15*) necessary to better define the kinematic characteristics of the mass movement in the Greci slope. A final configuration of the GPS network has therefore been obtained and it is shown in figure 2 (Gullà & *alii*, 2003).

The evaluation of deep-seated movements affecting slope is essential to understand the mechanisms governing their evolution over space and time (Cascini & *alii*, 1997a). The possibility of defining over the time the evolution of the displacement along representative verticals has enabled researchers to: a) detect the kinematics of the instability (movement, velocity, direction); b) frame the movements in a given kinematic phase (null movements, creep, pre-failure, failure, post-failure); c) reconstruct the location and the shape of the failure surfaces/zones and/or of the zones where large deformations are concentrated, that, accumulating over time, led to the formation of failure surfaces/zones.

To detect deep-seated movements authors used inclinometric verticals. These could be located on the basis of information obtained through the geomorphological study, and to the results of the measurement of superficial movements, where available.

In order to be able to draw significant indications from inclinometric measurements, in particular to assess whether displacements are very limited (in the order of a cm/y), a suitable number of surveys carried out over a sufficiently long period must be available (Cascini & *alii*, 1997a).

Although the methodology of measuring deep-seated movements in slope instabilities is well consolidated, the complexity of a correct implementation of inclinometric vertical tubes is usually neglected, above all for depths over 30 m, when drilling is carried out on rock masses made up of soils, weak and hard rocks, the latter being variously fractured.

In this case study, when the first (SO3) inclinometric vertical tube was designed and implemented (fig. 2), information inferred from the geomorphological analysis suggested the presence of a deep-seated slope instability at a depth of over 50 m. Geotechnical surveys indicated the presence of rock masses made up of a very irregular succession of geomaterials with portions where fractured to highly fractured rocks had a stony consistency and quite extended areas characterised by soil consistency (Sorriso-Valvo & *alii*, 1999). The conditions of the rock mass and the depth have made the implementation of the inclinometric vertical tubes particularly difficult.

In the vicinity of the inclinometric vertical, 100 m deep, located in the area of Piscopie, a borehole with piezometers (SO3b) has been carried out (fig. 4). Other boreholes have been equipped with piezometers (fig. 4), in order to collect data concerning pore-water pressure regime (Cascini & *alii*, 1997b).

The first data obtained by inclinometric measurements carried out in the locality of Piscopie suggested to set a second inclinometric vertical tube in the landslide of Acqua Fredda (SO1G), near the hamlet of Greci (fig. 4). Also in this case, the depth was of about 100 metres and a borehole in proximity of the inclinometric vertical has been equipped with piezometers (SO2G), fig. 4.

Monitoring superficial movements

During the GPS monitoring, the procedure has been modified to improve the effectiveness of measurement surveys.

In the first surveys, only three Ashtech double-frequency receivers had been employed. Subsequently, using more receivers have made measurements easier, through a new data collection scheme.

The initial surveys, using fast-static mode, had been carried out by locating two receivers on reference vertexes, while the third antenna (rover) engaged the monitoring points of the control network one after another, with three occupations for 10' session and 5'' sampling interval. The presence of obstacles on the horizon implied accurate planning of measurement sessions so as to enable signal reception under good satellite geometric conditions. The station of the control sub-network (*S1-S6*) and the stations of the reference network were all intrinsically connected through independent baselines obtained by means of static sessions of about 90', while the control points located in the area of Piscopie were connected each other and to the reference points with a triangular diagram, by means of independent baselines with sampling sessions of at least 60'. Over time, the greater availability of GPS instruments enabled us to test different measurement strategies up to the current scheme, whose centre is located on the most barycentric station between the reference points (*R4* in fig. 2). According to this approach, three receivers of the reference network continuously acquire data during the whole survey, while monitoring points were occupied at least twice with static sessions lasting almost two hours and with a sampling rate of 15''. This method on one side optimises survey times and, on the other, ensures greater accuracy in the calculation of coordinates, in particular for those points which had been previously measured in fast-static mode (Bonci & *alii*, 2004).

The data elaboration was carried out by considering the reference vertex R4 as a fixed point. The vertexes of the ref-

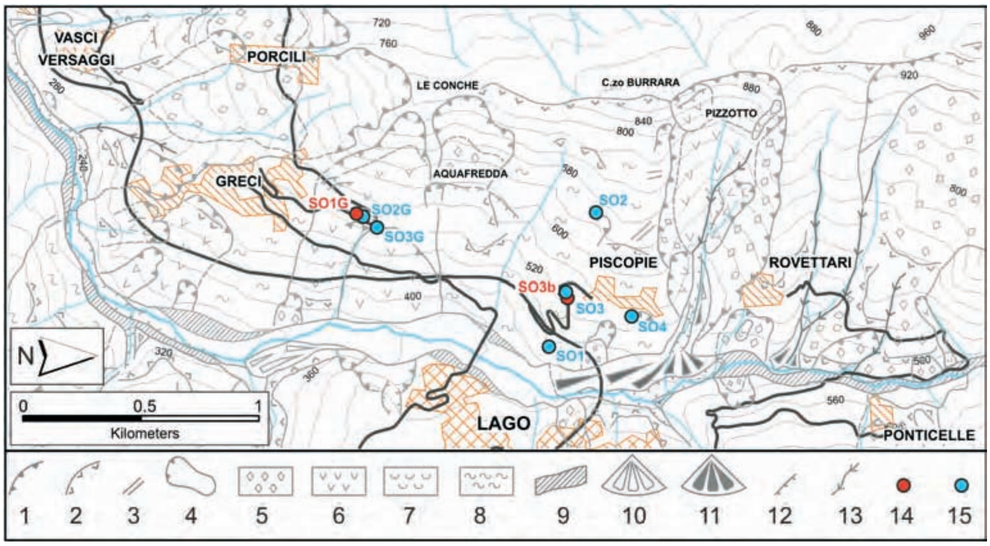

FIG. 4 - Landslides map and location of geotechnical monitoring network. LEGEND: 1) landslide main scarp; 2) sharp convexity or crest edge; 3) trench; 4) landslide body; 5) debris flow or earthflow debris; 6) rock or earth slide debris; 7) mudflow debris; 8) rock flow (*Sackung*); 9) 1951 river deposit; 10) inactive fan channel fill; 11) active fan; 12) erosion scarp; 13) down-cutting stream; 14) inclinometer; 15) piezometer.

erence network showing stability over time have been considered as datum. The processing has been carried out with several software programmes so as to test their potential and to assess whether quicker processing by means of a commercial software could have been considered effective in an early warning system. To that end, both the GeoGenius^{TM} software, comparing coordinates also without the statistical analysis of displacements significance, and the Bernese 4.2 (Beutler & *alii*, 2001) for data processing, have been employed. For the analysis of compensation and displacements significance, the NetGPS (Crespi & Sguerso, 1993) and Denet and Diffflh (Crespi, 1996) have been employed.

The comparison among the results obtained (Merli, 2001) pointed out that processing by means of a commercial software package can be considered as feasible, even if the calculation error of the baselines is underestimated, due to the fact that the software package does not consider the correlation among simultaneously detected independent baselines, when data processing is associated with rigorous adjustment and statistical analysis of the results, provided that the magnitude of the displacement accounts for some millimeters a year and that the initial surveys are processed also by means of a scientific software. Therefore, the combined processing methodology described above, has been considered as a suitable approach.

The accuracy of coordinates are indicated by the Standard Deviation (s) of measure values. It accounts for some millimetres in plan and usually lower than 5 mm at height, on average. Only some points (tab. 1), located in areas with limited visibility due to their morphology or vegetation, are an exception to the rule. From the analysis of tab. 1, it can be inferred that in the static sub-network, the values of s of adjusted coordinates have been improved in the latest surveys, after having modified the strategy in favour of a «star-like» scheme.

TABLE 1 - Values, average and maximum of the standard deviation of the geodetic coordinates (Lat, Long) adjusted with NetGPS for each measurement campaign in static GPS sub-network

	Year	**δ mean**	**δ max**
φ	1997	0.003	0.006
λ		0.002	0.004
h		0.005	0.008
φ	1998	0.004	0.007
λ		0.004	0.006
h		0.006	0.010
φ	1999	0.003	0.006
λ		0.003	0.006
h		0.005	0.010
φ	2000	0.004	0.006
λ		0.004	0.005
h		0.007	0.009
φ	2002	0.002	0.004
λ		0.002	0.003
h		0.005	0.008
φ	2004	0.002	0.003
λ		0.002	0.003
h		0.004	0.007
φ	2006	0.002	0.004
λ		0.002	0.003
h		0.004	0.007

The representation of the movements detected enabled us to analyse the trend of recorded displacements, fig. 5. The vectors clearly show the direction of the displacements. However, a greater variability of the azimuth in the first years is evident. This behaviour is clearly visible in *L9* e *L10* stations. These points are characterised by a velocity of about 1-2 cm/y, and the initial variability of the azimuth is greatly reduced with the static method of the last period. The point *L13*, which is characterised by greater displacements if compared to the previous points, does not display significant variability of the azimuth. Therefore it can be concluded that short sessions collected with fast-static method can determine displacements of some centimeters rapidly and reliably, while displacements of the order of one centimeter can be better detected through static sessions.

Finally, the behaviour of the reference station *R5* must be pointed out; in fact, it was located in an area considered stable upstream the Vallone Pizzotto. After some years of measurement, the check out of the stability of the reference network has revealed a movement towards the Val-

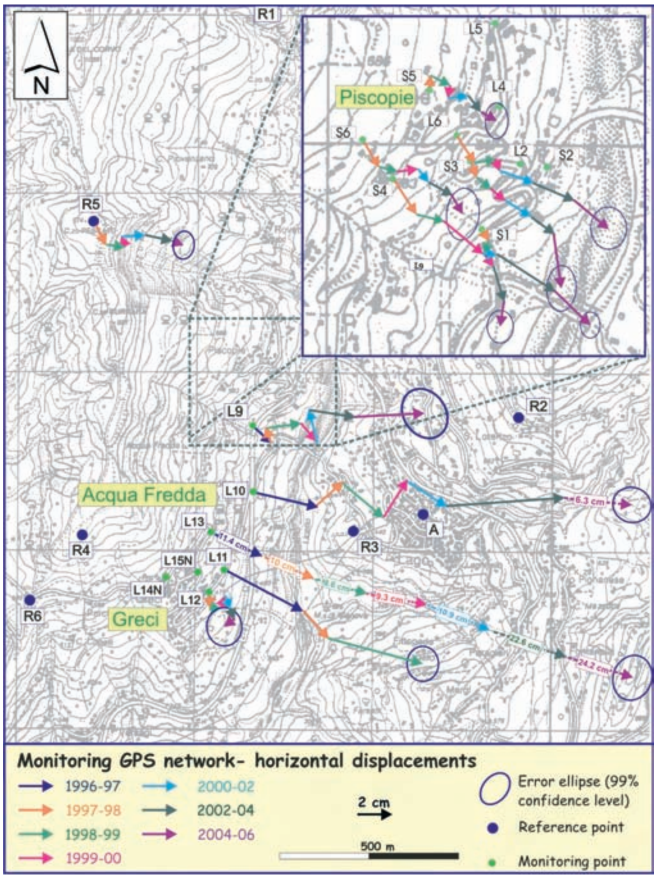

FIG. 5 - Horizontal displacements measured on GPS monitoring network for each period.

lone although the benchmark was located about a hundred metres from the crown of the Pizzotto landslide. Therefore, this benchmark has not been considered a reference point any longer, but just a control point.

For the points displaying statistically significant displacements, the vectors detected in the various periods have been reported in fig. 5; letter L indicates the benchmarks of the network measured in fast-static mode up to 2002 and subsequently measured in static mode, while letter S indicates the benchmarks of the static sub-network located in Piscopie. In this area some of the stations of the initial network are close to the benchmarks of the static sub-network; therefore, the measures shown here are those of the latter, given the fact that displacement rates in this sector are generally lower than 1 cm/y and static measurements are more reliable. To sum up, only the displacements which have a vector not completely falling within the error ellipses (with 99% confidence level) have been considered as significant.

Comparing the trends of the displacements cumulated over time of some very close benchmarks measured with both static and fast-static procedure (*S2* and *L1*, *S3* and *L3*), indicates that the measurements carried out on the whole network by means of the two procedures modalities, can be considered together (fig. 6).

By referring to the average velocity of the displacement cumulated over the whole measurement period for each benchmark, the stations can be classified into three groups with the following average rate: lower than 0.50 cm/y, between 0.50 cm/y and 2.00 cm/y, greater than 2.00 cm/y, fig. 7.

From fig. 7 the following can be inferred: in the Greci area a benchmark having average yearly velocity lower than 0.50 cm/y (*L12*) is present; the three benchmarks in the area of Acqua Fredda display average yearly velocity greater than 2.00 cm/y; about 2-4 cm/y in the peripheral areas of the surveyed zone (*L10*, *L11*), and about 10 cm/y in the central part of the same zone (*L13*).

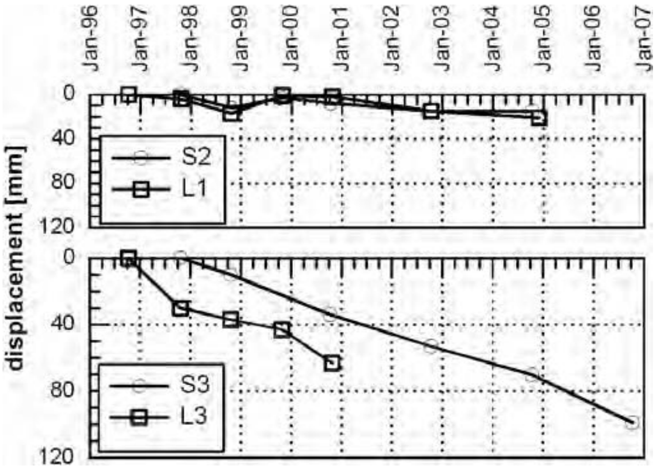

FIG. 6 - Comparison between the trends of the displacements cumulated over time on very close control points measured in static mode (*S2* and *S3*) and in fast-static mode (*L1* and *L3*).

Finally, in the area of Piscopie there are benchmarks displaying average yearly velocity between 0.50 and 1.70 cm/y (*S1*, *S3*, *S4*, *S5*, *S6*, *L6*, *L9*), while in some points (*L2*, *L4*, *L5*, *S2*) the measured displacements are not statistically significant; this finding is similar to data found in the Greci sector in *L14* and *L15*.

Deep-Seated Movements

Measurement along the inclinometric vertical tube in the area of Piscopie, started with zero reading in 1996 and regularly took place up to 2003, with 16 readings as a whole.

For the inclinometric tube implemented in the study area of Lago (CS) measurements took place one month after its installation and proceeded with close measurement in order to be able to substitute the zero reading. More-

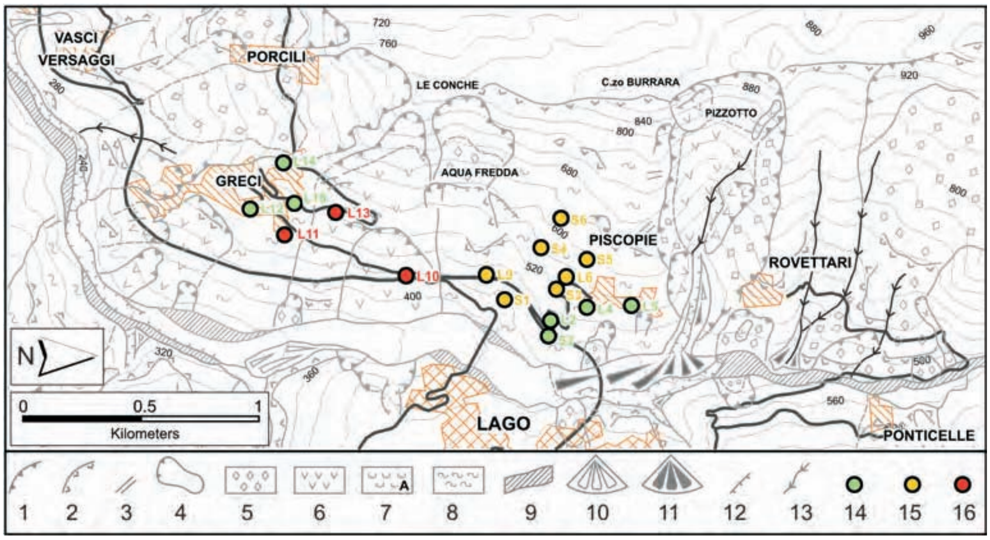

FIG. 7 - Control points classified according to the average velocity of the displacement. LEGEND: 1) landslide main scarp; 2) sharp convexity or crest edge; 3) trench; 4) landslide body; 5) debris flow or earthflow debris; 6) rock or earth slide debris; 7) mudflow debris; 8) rock flow (*Sackung*); 9) 1951 river deposit; 10) inactive fan channel fill; 11) active fan; 12) erosion scarp; 13) down-cutting stream; 14) average yearly velocity lower than 0.50 cm/y; 15) average yearly velocity between 0.50 cm/y and 2.00 cm/y; 16) average yearly velocity greater than 2.00 cm/y.

over, the closer measurements in the initial part of the monitoring activity was useful to optimize the recurrence of measurements in consideration of longer times which were required for the kinematic characterisation of the phenomenon under consideration.

Fig. 8 shows the deflections along the inclinometric tubes SO3 (from 1996 to 2003) and SO1G (from 2002 to 2003). As for SO3, it can be pointed out that the second useful reading enables to identify three separate sections characterised by different displacements: an initial segment, at a depth of about 28 meters, where a maximum displacement of 82 mm characterised by a uniform trend cumulates over the whole measurement period; a second section, with a thickness of 8 meters, characterised by a reduction of the displacement with a value of about 25 mm, and finally, a third section where the cumulated displacement of about 10 mm gradually fades out at a depth of 90 meters from the ground level, with a thickness of about 50 m. Fig. 8 shows the presence of clear shear zones between the first and the second displacement sections and between the second and the third displacement sections, where the movement stops. In the three sections, a wide range of velocities are identified, ranging from about 1.20 cm/y for the first section, 0.40 cm/y for the second section, and about 0.10 cm/y for the third section. According to mass-movement classification by Varnes (1978), movements occurring along the tube SO3 in the monitoring period are extremely slow.

The information obtained in the area of Piscopie suggested the implementation of a second vertical inclinometric tube in the area of Acqua Fredda (SO1G, fig. 8). Also in this case the tube reached a depth of about 100 meters and in its proximity a borehole equipped with piezometers has been located (fig. 4).

The measurements started in 2002 and stopped in 2003 when the progressive deformations at a depth of about 60 m hampered the passage of the inclinometric probe. Fig. 8 shows the inclinometric deflections from 2002 to 2003. These deflections confirm greater velocities in the site of Acqua Fredda (about 9 cm/y), as expected considering the quick blockage of the tube. Despite the short monitoring period, we can identify (fig. 8) three sections characterised by different movement modalities also for SO1G: in the first section, displacements cumulated over about 15 months of 11 cm at a depth of one meter, and of 9 cm at a depth of 22 m are present; these values indicate a substantially uniform deflection. A sharp reduction to about 6 cm of the displacement occurs in the two subsequent meters. In the second section the displacement is still uniform for a thickness of 36 meters; cumulated displacements range from 6 cm to about 5 cm, with a sharp reduction to less than 1 cm in the lowest three meters. In the third section residual displacement, smaller than 1 cm and reducing with the depth have been detected.

Along this vertical two clear shear surfaces are thus present between the sections at depth 22-24 m and 55 to 58 m, respectively; velocities are one order of magnitude greater than those detected along SO3 and, relatively to the measurement period, they allow researchers to classify the movements along the vertical tube as very slow (Varnes, 1978).

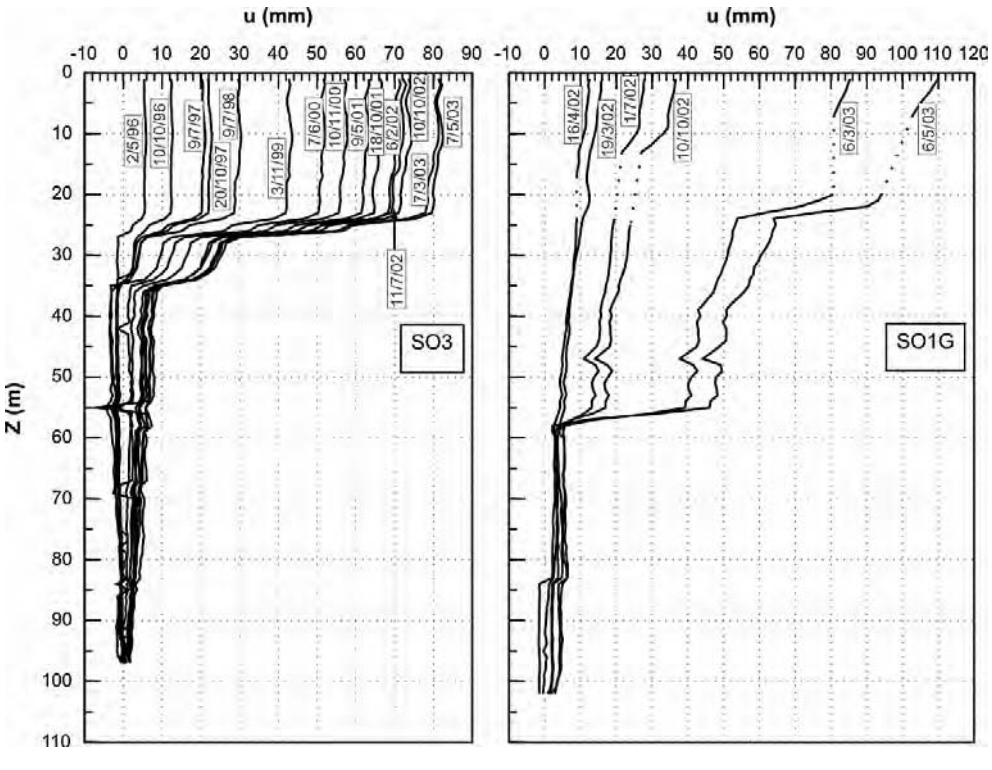

FIG. 8 - Deflections measured along the inclinometric verticals SO3 and SO1G.

Piezometric Measurements

Although groundwater circulation is difficult to define due to the complex structure and the great heterogeneity of geomaterials (probably as a consequence of mass movements), piezometric levels are referable to a single aquifer because piezometric levels display regular trends and seasonal variations (figs. 4 and 9), despite some singular fluctuations registered along the vertical SO4. In particular, piezometric levels measured in piezometers located in two of the three areas in which the study phenomenon is subdivided according to their kinetics, show variations in a range between 0.10 m and 2.50 m.

ANALYSIS AND INTERPRETATION OF MEASUREMENTS

In order to make the analysis more efficient, the congruence between superficial and deep measurements has been preliminarily assessed. Fig. 10 compares the trends of the displacements measured at one meter from the ground level along SO3 and SO1G and the two GPS points coinciding with these inclinometric verticals, or close to them (respectively *S3* and *L13*). It can be pointed out that for SO3 and *S3* there is a substantial consistency both in the trends and the magnitude of these displacements. As for SO1G and *L13*, considering the cumulated displacement as well as their directions, good consistency is also detected (fig. 10).

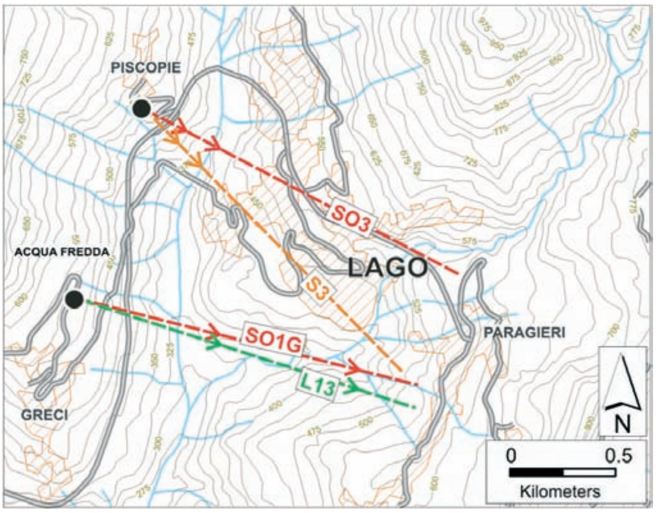

FIG. 10 - Comparison between horizontal displacements measured on the inclinometers (SO3 and SO1G) (at 1 m depth) and on the GPS control points (*S3* and *L13*), located at about 3 m from them.

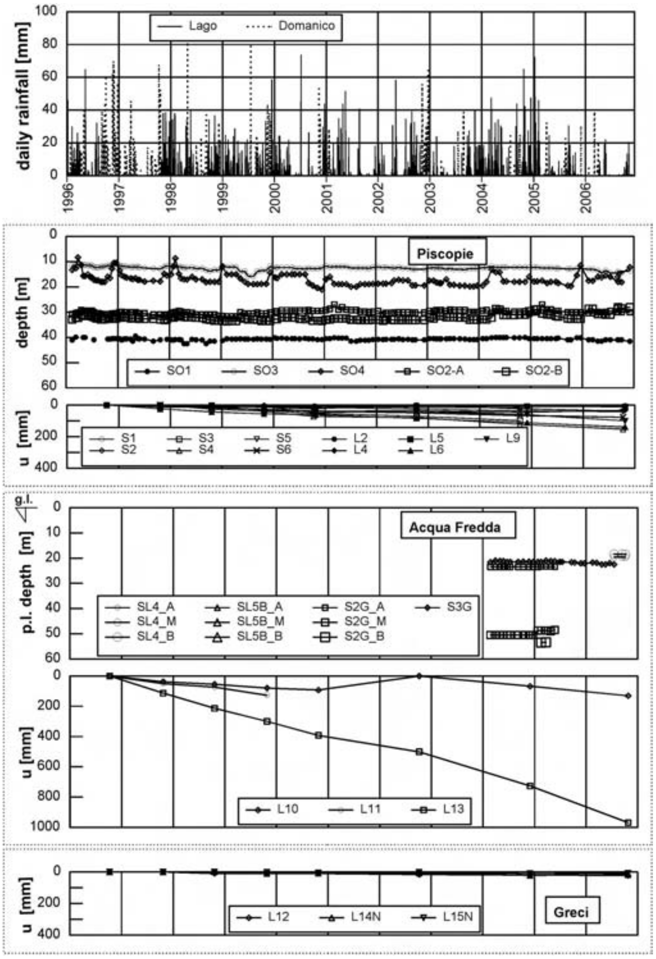

FIG. 9 - Trends of the displacements measured on GPS monitoring network compared with piezometric levels (piezometric level depth) and daily rainfall.

This data enables us to assume that the inclinometric deflections are reasonably representative of the areas in terms of shape, entity and progression of the displacements.

As for superficial displacements, it is clear (figs. 5 and 7) that the points located at Greci (*L12*, *L14*, *L15*) are characterised by non-significant displacements or by limited displacements (1-2 cm in about 10 years), which can be classified as extremely slow (Varnes, 1978). Therefore, the surveyed area can be considered as substantially stable, and, in fact, a quick examination carried out on the structures and infrastructures located in the same area, does not show any particular crack patterns. However, the indications drawn by the analysis of available data cannot exclude greater displacement velocities in areas downslope the GPS measurement points where some instable areas have been morphologically identified.

Northwards from Greci, the points showing greater displacements and located in the area of Acqua Fredda are clearly identified in figures 5 and 10. These are: point *L13*, which has been moving over ten years with constant direction and velocity, and shows a displacement of about 100 cm; point *L11*, showing a displacement of some centimeters per year in a direction ESE; and *L10* showing a kinematic behaviour similar to *L11*.

Figure 10 shows that *L13*, almost at the middle level of the slope, is located in an almost barycentric position in the Acqua Fredda landslide body. Displacement data concerning *L11*, located at a lower level than *L13*, suggest the extension of the landslide of Acqua Fredda beyond the right flak that was recognized on the base of geomorphological studies (fig. 7). *L10*, that, as already pointed out, shows a kinematic behaviour similar to *L11* and is at a lower level than the same, is located close to the left flank of the landslide of Acqua Fredda but in an area which has been morphologically identified as a secondary landslide body that is included in the larger landslide body of Acqua Fredda.

Ultimately, in the area of Acqua Fredda a slope sector has been identified as characterised by kinematic homogeneity and a quasi-stationary displacement velocity ranging between 9 cm/y and 5 cm/y. The depth and trend of the displacement over times enabled us to identify the very slow movement in the area of Acqua Fredda as a rock creep, involving a maximum depth of 60 m.

In the area of Piscopie smaller displacements have been identified as compared to the area of Acqua Fredda: the values obtained for the points *S2*, *L2*, *L4* and *L5* are not significant; those obtained for the points *S1*, *S3*, *S4*, *S5*, *S6* and *L6* display velocities between 0.5 cm/y and about 2 cm/y, with a general constant trend in SE direction. An accurate examination of the displacements during the surveyed periods indicates that for some points (*S3*, *S4*, *S6*), a reduction of the velocities has been registered in the period 2000-2002, as compared to the period 1999-2000 (*S3* from 0.96 to 0.84 cm/y, *S4* from 3.24 to 0.36 cm/y, and *S6* from 0.96 to 0.48 cm/y).

In *S1*, close to the foot of the slope, the displacement vector shows a different direction compared to the other points falling within the same area (fig. 5); such diversion has been probably caused by structural features, such as a harder layer or a fault plane, or similar local features. In *L9* the displacement measured is probably associated to local interactions with the retaining structure upon which it has been located and therefore, the displacement is not representative of the generalised gravitational movement of the slope.

In the area of Piscopie the kinematic characteristics observed enabled us to classify the movement as an extremely slow phenomenon affecting a maximum thickness of 40 m.

The results obtained for *R5*, considered as a reference point since 2000, indicate displacements cumulated over 9 years of 5 cm (with average velocity of 0.6 cm/y); thus the area above the crown of the Pizzotto landslide is in fact moving at present.

The limited variations in the piezometric levels generally measured for a long period (from about 0.10 m to about 2.50 m), also associated to considerable rainfalls and the trend of the displacement measured over time, both confirm that the ongoing movements of the slope, although differentiated in quantitative terms in the surveyed areas, should be associated to a slow gravitative creep movement (fig. 9).

The indications drawn from the first inclinometric measurements taken along the vertical SO3 and concerning the potential movement of the DSGSD driven by the subhorizontal tectonic structures characteristic of the area (rotation of about 90° of the direction of the displacements measured below 36 m, as compared to the direction of the displacements detected up to 36 m) (Sorriso-Valvo & *alii*, 1999) are not confirmed in the subsequent evolution; however, observation times are too short for a definitive analysis.

DISCUSSION AND CONCLUSIONS

In the past, the Greci slope has been affected by movements which, according to morphological evidence, are characterised by slow and continuous phenomena to which episodes of strong acceleration of the processes are associated; these processes show not yet defined, but long recurrence times.

Based on these quantitative elements concerning the kinematic scenario of the Greci slope, a monitoring network for the displacements has been developed as a component of a larger monitoring integrated network observing superficial and deep-seated displacements, pore water pressures, rainfall parameters etc.

The detection of a *Sackung*, which was not clear on the basis of morphological evidence, has highlighted the importance of defining a sound kinematic scenario for such a peculiar type of mass-movement. Although the detected slope conditions do not indicate that a catastrophic evolution of the *Sackung* processes is likely to take place in the short run (Sorriso-Valvo & *alii*, 1996; 1999), the areal extention of the phenomenon urges the definition of useful elements and instruments to characterise and control similar situations with different levels of accuracy. The general aim of this study is to define a solid reconstruction of the slope dynamics.

The work carried out leads to some important methodological conclusions. Besides confirming the need for a detailed set of geological, geomorphological, hydrogeological and historic data, the design of such networks (with special reference to complex geo-environmental contexts and to the type of instability which may have a potential significant impact on the territory) must include the integration and reorganisation of displacements monitoring network that must be planned and developed according to the results of the initially collected measurements, and to the adjustments of forecast models gradually arranged. The constant attention to optimising the number of control points has been achieved through careful evaluation of representativeness of each of them, relocating control points when advisable.

Some criteria that had been adopted in the design stage of the GPS network, have subsequently proven to be fundamental to keep the network in working order and to reach the expected results. Selecting the sites where GPS benchmarks could be installed, was based on the structural, geological and geomorphological layout of the area. Geological and geomorphological knowledge of the study phenomenon has been fundamental for the selection of the reference stations, since these features enabled researchers to detect some points outside the part of the slope which had been considered affected by the instability.

As for measurement procedures, the surveys carried out so far have highlighted that the GPS fast-static techniques, although less accurate in determining the coordinates of control points, enable to obtain completely satisfactory results with displacement velocities over 2 cm/y. Vice-versa, measurements in areas characterised by displacement rates less than 2 cm/y must be performed with the static modality.

When planning measurement sessions, it is more efficient to follow a strategy with a star-like structure whose center is located at the most barycentric stable point. Such configuration enables to minimize change in height between the benchmarks and, therefore, to reduce the tropospheric effect.

As for the processing step, our experience shows that good quality commercial software packages, with user friendly and efficient interfaces, are suitable for data processing also in complex situations. When, as in the case study, short baselines are used, data processing can be carried out by using only the L1 frequency and broadcast ephemeris. For the GPS network adjustments and significance analysis, it is advisable using scientific software packages enabling to find the weights to be assigned to each base taken into account and to detect and eliminate outliers also by means of an iterative procedure.

There are clear and consolidated methodological references for the measurement of deep-seated displacement in unstable slopes (Cascini & *alii*, 1997a). However, different aspects related to the implementation of the equipment and to measurement interpretation must be dealt with and defined when studying instabilities that are characteristic and representative of definite geo-environmental contexts, so as to provide useful references to solve, and to study, in a more efficient way problems caused by similar instability phenomena. The final goal is to make easier and more efficient the study of mass-movements to render intervention measures more efficient too. Especially for complex, large-scale mass movements such as the one under investigation. The indications inferred from studies carried out on mass movements showing features that allow us to group them in study categories (typify), should permit to draw up guidelines to define survey, modelling and analysis strategies and therefore to plan efficient actions for risk mitigation/reduction, with special reference to the management of emergencies.

Results obtained in this study are of great importance because they allow eliminating most uncertainities in understanding the dynamics of the complex superficial and deep-seated displacement pattern of the studied phenomena.

The elements acquired suggest that the Greci slope is affected by a DSGSD moving with maximum velocity of 0.5 cm/y for thicknesses of about 100 meters. In some areas, this phenomenon finds direct confirmation also on the surface (Piscopie and Greci).

In the area affected by the DSGSD, some medium deep (Piscopie) and deep (Acqua Fredda) mass movements have been detected and they progress with a prevalently translational slide mechanism and with constant velocities (constant for the unstable volume) of 1 cm/y and 10 cm/y, respectively.

Medium deep and deep-seated landslides sometimes occurring in areas affected by deep-seated slope deformations, may rapidly accelerate their velocity and significantly affect structures and infrastructures, as confirmed by recent instability phenomena which damaged some building works located close to the measurement point *L10*, fig. 5.

The results of this study enable a fine-tuning of geotechnical model for the case study of Greci slope (Silvestri, 2006) and the potential employment of the integrated monitoring network for control and alert purposes.

Cracks distribution on buildings and roads suggests the need to proceed with a joint use of structural and non structural actions for risk mitigation and reduction. This indication could be generalised for mass movements involving relevant volumes of rocks moving at an extremely low or low velocity prior to the pre-failure phase.

Based on the average displacement velocity of the whole measurement period, and on the quick assessment of the effects on structures and infrastructures built on the outlined areas, risk conditions can be assessed by expert evaluation.

In conclusion, the integrated monitoring network is therefore essential for defining intervention strategies. The development of an integrated monitoring network, in fact, allowed to infer some indications for the Greci slope and in general for complex, slow-moving mass movements; as a consequence the results in terms of landslide risk mitigation/reduction can be improved both at the stage of study and definition of the geotechnical model and in the phase of selection and dimensioning of structural and non structural measures.

The methodological results obtained in this case study are therefore important, from both study and applicative viewpoints.

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