DOI: 10.4408/IJEGE.2017-01.S-09

GEOMECHANICAL ANALYSIS OF UNSTABLE ROCK WEDGES BY MEANS OF GEOSTRUCTURAL AND INFRARED THERMOGRAPHY SURVEYS

Giovanna PAPPALARDO(*), Simone MINEO(**) & Domenico CALCATERRA(**)

(*) Università di Catania - Dipartimento di Scienze Biologiche, Geologiche e Ambientali - Corso Italia, 57 - 95129 Catania, Italy
(**) Università degli Studi di Napoli Federico II - Dipartimento di Scienze della Terra, dell'Ambiente e delle Risorse - Largo San Marcellino, 10 - 80138 Napoli, Italy
Corresponding author: simone.mineo@unina.it

EXTENDED ABSTRACT

La stabilità dei versanti rocciosi rappresenta una tematica di rilevante interesse scientifico, poiché i fenomeni franosi che caratterizzano tali pendii sono annoverati tra i principali fattori di rischio naturale. In generale gli ammassi rocciosi sono assimilabili ad un mezzo discontinuo, la cui qualità geomeccanica è influenzata dalla presenza di discontinuità e dalle loro caratteristiche. Per questo motivo, il grado di fratturazione di un ammasso roccioso è l'oggetto principale di studio in caso di analisi di stabilità. Il censimento e la descrizione delle discontinuità presenti lungo un versante rappresenta un approccio metodologico ormai consolidato, noto con il nome di rilievo geostrutturale, e normato da raccomandazioni internazionali (ISRM, 2007). Questo, se eseguito a regola d'arte, consente di misurare direttamente in situ i parametri necessari per lo studio della stabilità e garantisce elevati livelli di affidabilità in termini di risultati. Tuttavia, non sempre le condizioni del territorio consentono un accesso diretto al versante da studiare; basti pensare a settori di pendii a quote elevate, falesie costiere, aree impervie. Per questo motivo negli ultimi decenni sono state sviluppate tecnologie che consentono lo studio dei versanti operando da remoto, talvolta con elevato dettaglio. Nello specifico la Termografia ad Infrarossi è, da qualche anno, oggetto di ricerche scientifiche mirate alla sua applicazione all'analisi della stabilità dei pendii. Infatti, pur essendo una tecnica largamente utilizzata in diversi settori scientifici, quali la medicina, la botanica, la fisica e l'ingegneria (Hudson, 1969), il suo utilizzo nell'ambito della geomeccanica ha ancora carattere pionieristico. Baron *et alii* (2012) hanno utilizzato la Termografia ad Infrarossi per mappare fratture aperte lungo versanti instabili della Repubblica Ceca e dell'Austria, sfruttando la differenza di temperatura tra l'interno delle fratture e l'ambiente esterno. Mineo *et alii* (2015a) hanno acquisito immagini termiche ad infrarossi per valutare la presenza di aree instabili lungo un versante roccioso già interessato da frane, riuscendo ad identificare potenziali aree-sorgente di movimenti franosi sulla base del diverso comportamento termico degli elementi lungo il versante (vegetazione, detrito, roccia nuda). Gli incoraggianti risultati raggiunti hanno portato a testare la diretta applicabilità di tale metodologia di indagine al rilievo della fratturazione di ammassi rocciosi. In particolare Mineo *et alii* (2015b) hanno eseguito rilievi con termocamera su versanti rocciosi in diverse fasi della stessa giornata, dimostrando che la fratturazione influenza la propagazione del calore nell'ammasso, quindi la sua temperatura superficiale.

Il presente lavoro rappresenta un ulteriore approfondimento su tale tematica, con particolare riferimento all'analisi di cunei rocciosi in ammassi intensamente fratturati. Lo studio è stato condotto su versanti campione della Sicilia nord-orientale che presentano configurazioni cinematiche di criticità; nel dettaglio sono state scelte due stazioni di misura su affioramenti carbonatici del Lias, in corrispondenza di cunei di roccia incipienti o già franati, con l'obiettivo di reperire informazioni da integrare al rilievo geostrutturale di campagna. I termogrammi sono stati acquisiti in condizioni di totale oscurità, in una notte estiva caratterizzata dall'assenza di precipitazioni, ad una distanza media di 3-4 m dall'ammasso roccioso. L'analisi dei termogrammi conferma l'influenza della fratturazione sull'output termico, in quanto le aree a temperature maggiori (anomalie positive) sono riconducibili a porzioni più fratturate dell'ammasso e/o a discontinuità aperte, mentre i settori a temperature inferiori (anomalie negative) sono caratterizzati da una fratturazione meno evidente e/o da una morfologia liscia e regolare.

Inoltre, procedendo all'elaborazione digitale dei termogrammi è stato possibile evidenziare particolari anomalie legate a specifici intervalli di temperatura, individuando non solo i volumi di roccia cuneiformi, ma anche aree estremamente fratturate e potenzialmente instabili. Tali informazioni sono state utilizzate anche per stimare numericamente i potenziali volumi di roccia in equilibrio precario. Nel caso specifico, questi sono localizzati sia ai margini dei cunei, sia all'interno delle aree-sorgente, sottolineando quindi la predisposizione di tali fenomeni franosi alla riattivazione mediante mobilizzazione di nuovo materiale.

I risultati raggiunti rappresentano un'ulteriore validazione della Termografia ad Infrarossi come metodologia di indagine a supporto del rilievo di versanti rocciosi, arricchendo la casistica scientifica nel settore della geomeccanica e ponendo le basi per studi di approfondimento futuri su ammassi a diverso grado di fratturazione e litologia.

ABSTRACT

This research aims to assess the potential of InfraRed Thermography employed for the remote survey of rock masses, with particular reference to the analysis of rock wedges. The application of such technique in the rock mechanics is a relatively new practice, and only few data are available in the international literature. In this paper, we provide an interesting case study aimed at coupling InfraRed Thermography with geostructural surveys for the stability analysis of rock slopes in northeastern Sicily. Chosen rock masses are characterized by intense fracturing and show relevant criticalities from the stability point of view. In particular, the main feature occurring along the slopes is a series of rock wedges driven by two or three discontinuity systems. The analysis of thermograms returned interesting matches between geomechanical features and thermal outputs, demonstrating that fracturing affects the thermal behavior of rock masses. The digital processing of images allowed highlighting anomalies related to specific ranges of temperature, thus individuating not only the rock wedges, but also highly fractured and potentially unstable sectors. Achieved results allow validating the application of such methodology in support of a stability analysis, providing further knowledge in this field of the rock mechanics.

Keywords: *InfraRed Thermography, rock wedge, rock mass, stability analysis, geostructural survey*

INTRODUCTION

Instability of rock wedges is a common problem in engineering geology regarding both slopes and underground excavations. Such kinematic features are formed by the intersection of at least two discontinuities and the slope face (Hoek & Bray, 1981). Their description, as well as a general rock mass characterization, is often subject to uncertainties due to the limited data typically available during the site survey and to the great variability of the rock properties (e.g. Warburton, 1981; Goodman, 1989; Low, 1997; Wang & Yin, 2002, Jimenez-Rodriguez & Sitar, 2007). The geostructural survey is an essential procedure for the assessment of geomechanical quality and stability of a rock mass, because it ensures a systematic and quantitative description of discontinuities (Ferrero *et alii*, 2009). However, the accuracy of such methodology may be influenced by the fracturing condition affecting the slope. In fact, rock masses are often characterized by crushed or heavily jointed sectors (Palmstrom, 2005), where a detailed mapping of all the discontinuities is not always feasible. For this reason, it is useful to couple geostructural survey with innovative techniques allowing the evaluation of geomechanical features under different points of view. In particular, InfraRed Thermography (IRT) is a well-known methodology allowing the determination of the temperature of an object by capturing its emitted infrared radiation (Shannon *et alii*, 2005). Its pioneering application in rock mechanics proved a useful support to the in situ survey. Recent outcomes were presented by WU et al. (2005), who used IRT to assess the integrity of rock mass behind a shotcreted slope. Baron *et alii* (2012) applied this technique for mapping open fractures along unstable rock slopes of Czech Republic and Austria under a blanket of snow, while Teza *et alii* (2012) proposed a method based on the analysis of thermal images taken during the night cooling of a rock cliff. Mineo *et alii* (2015a) employed IRT to individuate potentially unstable areas along a slope in northern Sicily. Furthermore, Mineo *et alii* (2015b) provided preliminary results on the application of IRT for the study of discontinuities at intensely jointed rock masses, suggesting further campaigns to deepen the knowledge in this field. In this perspective, with the aim of testing the utility of IRT for the survey of rock wedges, we carried out a shooting campaign in eastern Sicily (Fig. 1a), where the complex tectonics strongly contributed to the fracturing of rock masses. The study area is located in the southern sector of the Calabria-Peloritani Orogen, where slope stability is one of the main engineering geological problems. In particular, the surveyed rock masses are dolostone outcrops affected by heavy jointing and crushed portions. Such a structural configuration is responsible for the frequent rockfalls of the study area, mainly occurring through wedge sliding (Pappalardo & Mineo, 2015).

GEOLOGICAL SETTING

The Calabria-Peloritani Orogen is a segment of the southern Alpine orogenic belt linking the Apennine chain, to the north, with the E–W-trending Maghrebian belt, to the south (Cirrincione *et alii*, 2012). From the structural point of view, it is a nappe-pile edifice composed of distinct tectonic slices of metamorphic basement (remnants of Hercynian and Alpine orogeny) and Mesozoic-Cenozoic sedimentary covers. Its most recent evolution is strictly linked with the coexistence of extensional and compressional phenomena, as a consequence of the Tyrrhenian basin opening. This caused the activation of a regional strike-slip tectonics, averagely oriented NW-SE, known as South Tyrrhenian System (Finetti *et alii*, 1996), active from upper Tortonian and locally still active, especially in the central and eastern portion of the Orogen.

The study area, located in north-eastern Sicily, hosts lithologies ascribable to the Longi-Taormina Unit (Lentini *et alii*, 2006) (Fig. 1b). The bottom of the unit is represented by a Variscan epimetamorphic basement made of metabasites and porphyroids, which are the oldest eruptive products of the Paleozoic sequence of Peloritani Range (Trombetta *et alii*, 2004). With reference to the sedimentary cover succession of the study area, the oldest portion is represented by Upper Triassic fluvial “Verrucano-type” deposits, followed by a few meters of Hettangian greyish continental and marine sandstones, and by neritic carbonates, which rapidly evolve to pelagic limestones. In particular, lower Liassic greyish-white limestones and dolostones in carbonate platform facies represent the most relevant portion of the sedimentary covers of the Unit cropping out in the study area, where the maximum thickness was surveyed (Lentini *et alii*, 2006). The top of the local stratigraphic succession is represented by alternated marly limestones and marls belonging to the "Medolo" Formation.

METHODOLOGY

An Infrared Thermography shooting campaign was carried out at two carbonate rock masses, which were named Wedge Station 1 (WS1) and Wedge Station 2 (WS2) (Fig. 1b), characterized by a kinematic predisposition to fail through wedge sliding. In particular, WS1 is a heavily jointed rock slope showing crushed portions formed by the intersection of several discontinuity systems (Fig. 2a), while WS2 has already been affected by a rockfall, which left an evident mark of its source area (Fig. 2b). A preliminary geomechanical characterization was achieved by carrying out geostructural surveys, according to ISRM (2007) recommendations, which allowed describing the fracturing of the slopes and assessing the potential failure modes according to Hoek & Bray (1981). Among these, our attention was focused on wedges, which represent the most widespread instability feature in the studied sector. Once achieved a good knowledge on the stability of the slopes, IRT was tested with the

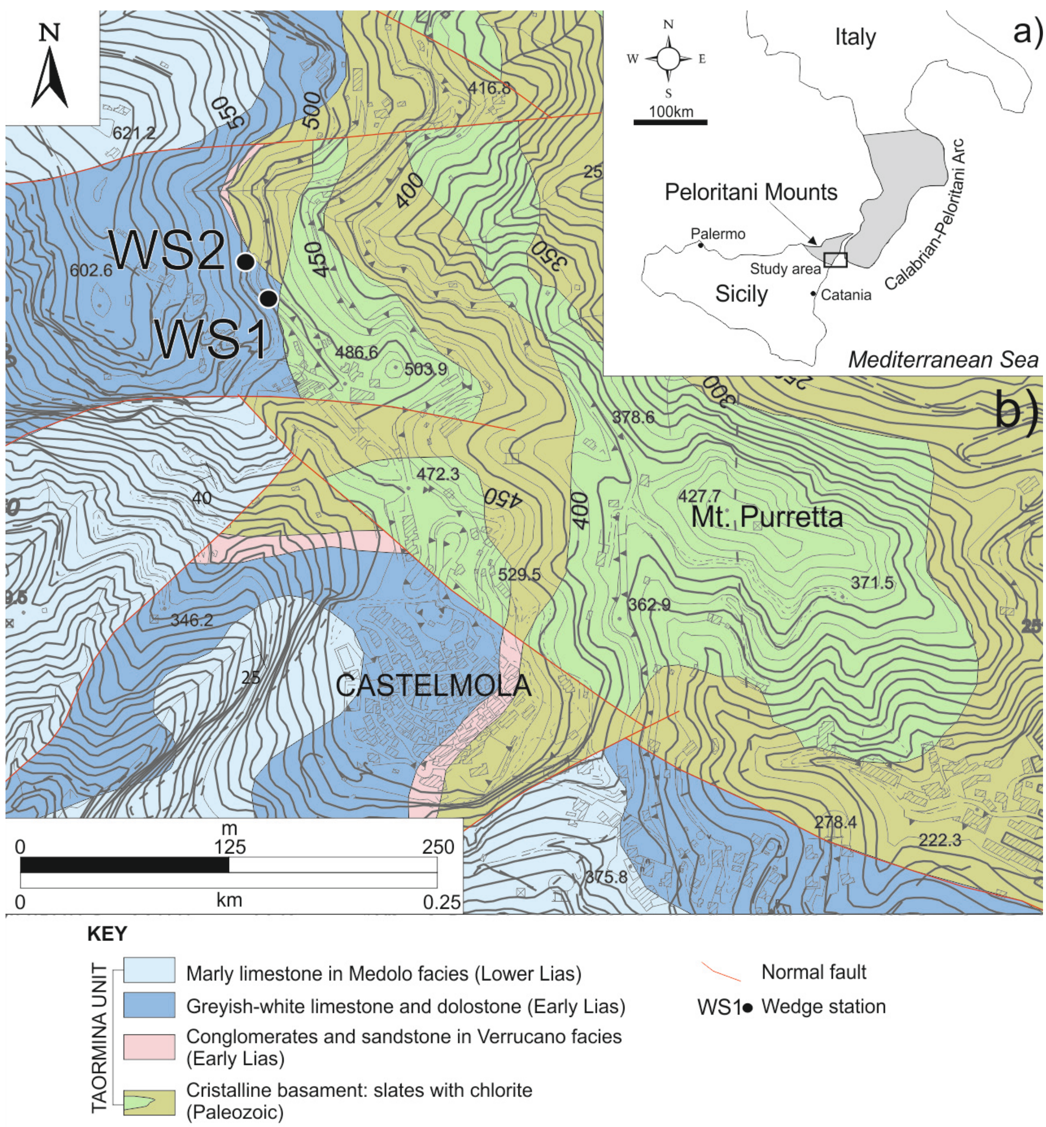

Fig. 1 - Geographical location (a) and geological map (b) of the study area, modified after Pappalardo et alii (2014)

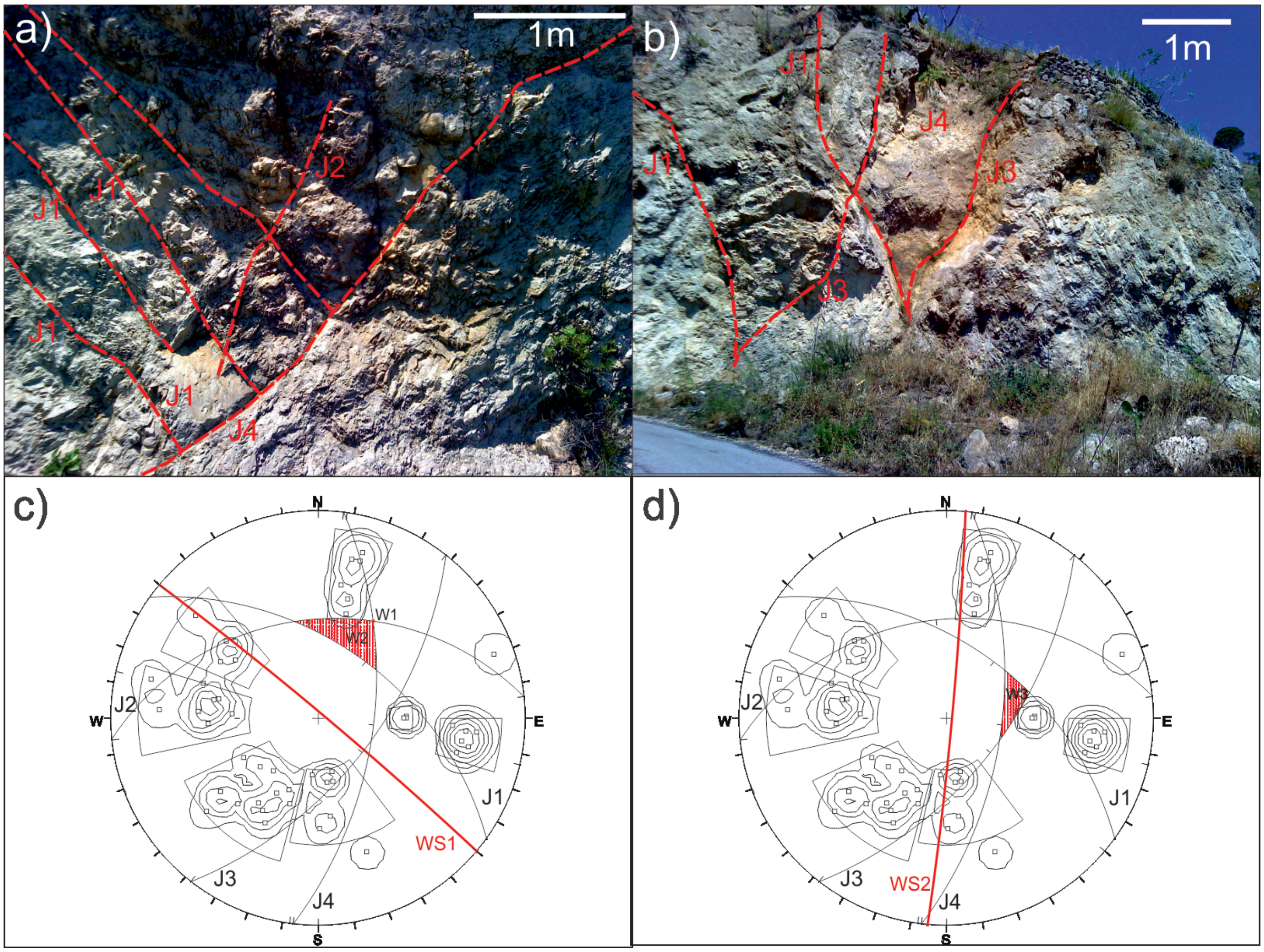

Fig. 2 - Photos of the surveyed rock masses taken in daylight, (a) WS1 (b) WS2, with their representative stereonets showing the main discontinuity systems (c-d)

purpose of evaluating whether its application could bring further useful information.

The IRT survey was carried out in nighttime, during the dry season, when the image acquisition is likely to be undisturbed by any parasite radiation generated by either natural or artificial light sources. An infrared camera, with a spectral range of 7.5–13 µm, was employed for the survey. It is characterized by an accuracy calibrated within +/– 2°C or +/– 2% of reading, a range of measurable temperature between -20° and +120°C and an integrated laser pointer. A tripod ensured the stability of the camera, which was placed 3-4 m away from the slope.

Thermal images (i.e. thermograms) are color-scaled pictures representing a map of the temperature variation. Each image consists of a matrix of pixels with a corresponding temperature value. These were digitally processed to achieve the best representative output, as well as to isolate different temperature ranges. In this way, all the features related to the variation of temperature along the rock masses were highlighted and linked with the most relevant geomechanical aspects.

GEOSTRUCTURAL SETTING AND WEDGE MODELLING

The geostructural setting of the studied rock masses is characterized by 7 main intersecting discontinuity systems, responsible of the high degree of fracturing of the rock. Discontinuities, whose spacing ranges from 2 to 60 cm and openings from 0.1 to >5 mm, are usually filled with weathered material or calcite and the joint surfaces are mostly smooth or undulated, with a Joint Roughness Coefficient (JRC) ranging from 2 to 12. Such discontinuities are often related to the regional fault systems occurring in this sector of Sicily. Small and micro-caves due to carbonate chemical dissolution occur along some slopes, while no considerable karst features have been surveyed in the outcrops of the study area. Representative stereonets are

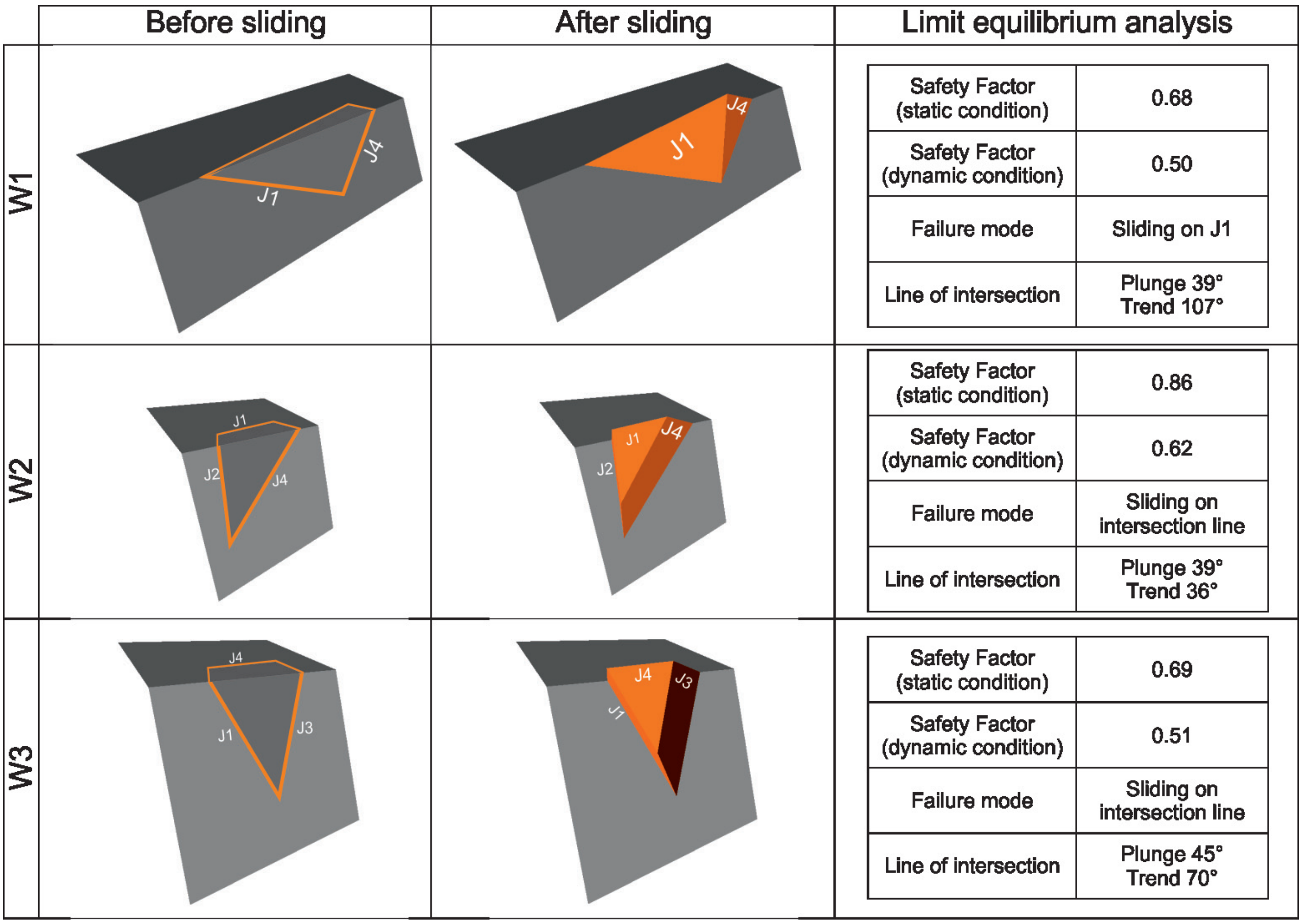

Fig. 3 - 3D models of the main wedges

reported in Figures 2c-d, where the predisposition of the slopes to fail through wedge kinematics is highlighted. In particular, the most critical wedges are formed by the intersection of 2 and 3 discontinuity sets. Specifically, WS1 is affected by two unstable wedge configurations: Wedge 1 (W1) is formed by the intersection of J1 and J4 sets. It is an asymmetric wedge, whose sliding would be driven by J1 plane, due to its dip-slope geometry (Fig. 3). Estimated unstable volume, based on in situ measurements, is about 12 m^3. The second wedge (W2) is formed by the intersection between J2, J4 and J1 sets; in this case, J1 acts as a tension crack enhancing the sliding of the unstable volume (Fig. 3).

At WS2, the source area of a previous event was surveyed. It is bordered by sets J1 and J3, while J4 system acts as a tension crack since it strikes almost parallel to the slope face. It is likely that the rock volume, which used to occupy the source area according to W3 model (Fig. 3), slid on plane J4 driven by the line of intersection. The same wedge typology is in an incipient state next to the source area (Fig. 2b). It is formed by the same discontinuity systems and holds a volume of potentially unstable rock of about 8 m^3.

To assess the stability of such wedges from a numerical point of view, a limit equilibrium analysis was performed according to Kovari & Fritz (1976). Resulting factors of safety, under dynamic condition, are 0.50, 0.62, and 0.51 for W1, W2 and W3 respectively, highlighting the instability related to the above mentioned structures.

IRT SURVEY

In nighttime, all the heat gained by the rock masses during the day is released through the discontinuity systems. In this view, positive anomalies are related to fractures, caves and hollow parts, where the warmer air is preserved, while negative anomalies indicate low fractured planes, as well as weathered portions and jutting sectors (Mineo *et alii*, 2015b).

WS1 survey

The surface temperature of the rock ranges between 18 and 20.9°C. The first immediately evident element is a positive anomaly, with a linear shape and an inclination of about 50°,

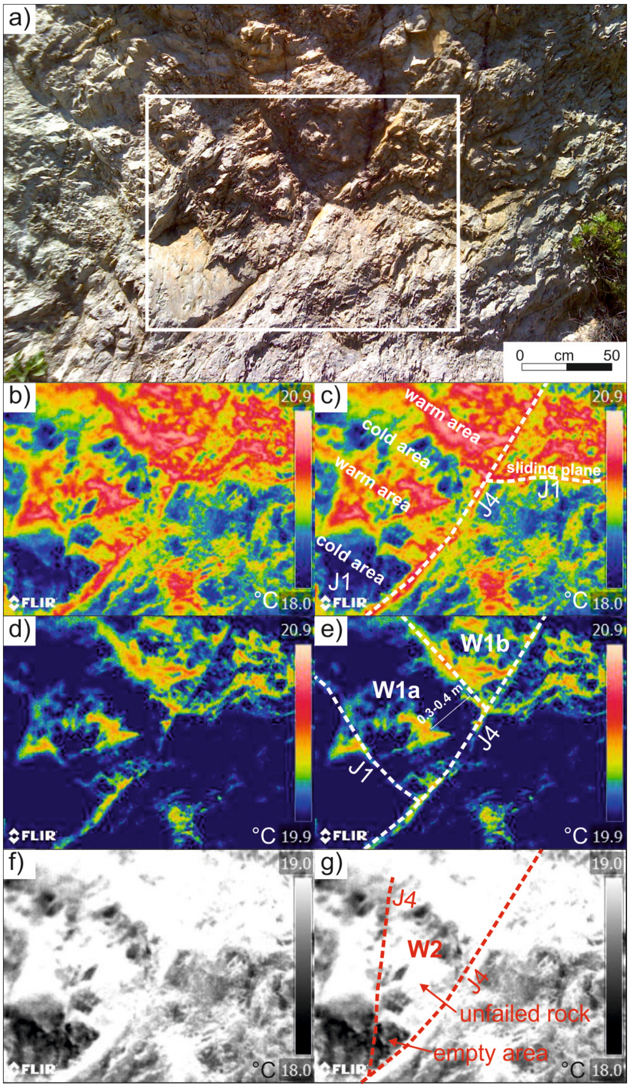

Fig. 4 - WS1 rock mass a) photo taken in daylight, rectangle encloses the area of thermograms; b) thermogram 18-20.9°C, c) thermogram 18-20.9°C with particular elements highlighted; d) thermogram 19.9-20.9°C; e) thermogram 19.9-20.9°C with particular elements highlighted; f) thermogram 18-19°C; g) thermogram 18-19°C with particular elements highlighted

cutting obliquely the whole thermogram (Figs. 4a-b-c). This is the trace of a discontinuity belonging to the J4 family, a persistent set characterized by openings ranging between 1 and > 5 mm. Along with this structure, other anomalies occur within the image. In fact, it is possible to notice warm areas alternated to cold sectors. In particular, the lowest temperatures have been recorded at a smooth and low fractured plane belonging to the J1 system; on the other hand, the highest temperature characterizes the heavily fractured sectors, where the chaotic intersection of fractures leads to the formation of small, sharp rock volumes.

Another feature highlighted by the IRT analysis is the presence of a sub-horizontal discontinuity separating two sectors with different temperature. This is related to the intersection between J1 and the slope face. Because of the dip-slope geometry of J1, in this case, it acts as a sliding plane, which is likely to drive a rock sliding involving the fractured material on the top (warm area).

In order to better analyze the thermal anomalies and to define their geometry, we have performed a digital processing of the image so to isolate different ranges of temperature. In particular, positive anomalies were highlighted by selecting only the highest temperature range (19.9-20.9°C), thus canceling the contribution of the lowest temperatures. In the resulting thermogram (Figs. 4d-e) the presence of J4 discontinuity is more evident. Furthermore, its trace is almost perpendicular to J1 forming two relevant rock wedges, according to the W1 model (Figs. 4d-e). In particular, W1a is the widest wedge, while W1b is a small wedge occurring within the area of W1a. This has to be regarded as a critical configuration, since an unstable volume of rock (W1a) is further fragmented into smaller volumes driven by the same discontinuity system. The analysis of thermogram suggests also the presence of a warm region within W1b area. This represents a portion of intensely fractured material enclosed between two intersecting fracture systems, which is likely to have already been subject to local decompression phenomena. Such an element cannot be easily detected during a geostructural survey, especially if the rock mass is affected by a high degree of fracturing. By coupling this information with the factors of safety previously estimated, a potentially dangerous scenario is outlined. In fact, this wedge is unstable from the limit equilibrium point of view and it holds fractured and unstable material. Thus, we can state that it is likely to be close to failure. Moreover, even W1a is affected by a warm region in its lower sector. This can be read either as another volume of unstable material, or as a further discontinuity belonging to the same system, since it shows a shape elongated according to the direction of J1.

The same thermogram is useful also to retrieve information on the spacing of the main sets, which is one of the key parameters to take into account for a rock mass classification (Bieniawski, 1989). For example, J1 spacing estimated from Figures 4d-e is about 30-40 cm, which is in accordance with geomechanical data. This is a useful advantage of such a survey methodology, especially when direct geostructural surveys are not feasible (e.g. coastal cliff, high rock masses).

A further processing of the image was performed in order to remove the contribution of the highest temperatures. In this way, we aimed to highlight thermal anomalies occurring in a lower range of temperature. A 18-19°C thermogram is reported in Figures 4f-g, where, with the help of grayscale, a slight sub-vertical discontinuity is outlined. It belongs to J2 set and is characterized by a small opening. However, it intersects J4 forming an asymmetric wedge according to the W2 model. It is noted how the lowest portion of the wedge has already failed, baring the smooth dip-slope J1 plane, which acted as a sliding surface (see empty area in Figs. 4f-g). In this case, the help of IRT comes with the characterization of the un-failed material enclosed within the wedge area. This is represented by positive anomalies, index of intense fracturing and, probably, decompression, thus suggesting its proximity to failure.

WS2 survey

The temperature of the rock face ranges between 17.3 and 22°C, where the lowest values are related to a vegetation band mainly occurring at the foot of the slope (Fig. 5a). The thermogram shows a chaotic alternation of positive and negative anomalies, apparently with casual shapes, where two main discontinuities bordering a source area of a wedge can be individuated. This was left by a movement occurring according to the W3 model in Figure 3. Two of the three systems, belonging to J1 and J3 are highlighted by warm colors, while J4 dip-slope plane is the internal face of the source area. The highest temperatures are recorded within the source area and at its sides (Figs. 5b-c).

By narrowing the range of temperature, to highlight the highest values, a better definition of the positive anomalies is achieved. J1 and J3 traces are clearly visible (Figs. 5 d-e); in particular, J3 appears as a bare plane with an intensely fractured external edge. Moreover, IRT shows how, at the slope face, the traces of other discontinuities occur next to the source area. Such traces, parallel to the main systems, have a close spacing and border positive anomalies, highlighting a heavy fractured rock around the source area. This is an important hint retrievable by the study of IRT images, because such areas are likely to be potential enlargement sectors of the wedge, thus suggesting possible reactivation of the landslide movement. By scaling the thermogram and taking advantage from the depth of the source area, we measured the volume of the rock material potentially involved in future landslides. It is about 0.75 m^3 at the right side of the wedge. Such value is indicative only of the area caught by IRT and may be affected by variations related to the persistence and geometry of the planes and to the fracturing of the unstable material. Nevertheless, it represents a suitable value for a preliminary estimation of the entity of potential failures.

Another element requiring attention is represented by the positive anomaly occurring at J4 plane, within the source area. As in the case of WS1, this anomaly can be related to fractured and unstable material, which underwent decompression phenomena especially after the first landslide event. This is a further hint provided by the IRT analysis, which suggests a further potential detachment area in a future reactivation of the failure. This would lead to retreat phenomena of the slope. In this case, J4 plane will play a key role, because the mobilized material will slide on it and, subsequently, along the intersection line of J1 and J3, according to the W3 model (Fig. 3).

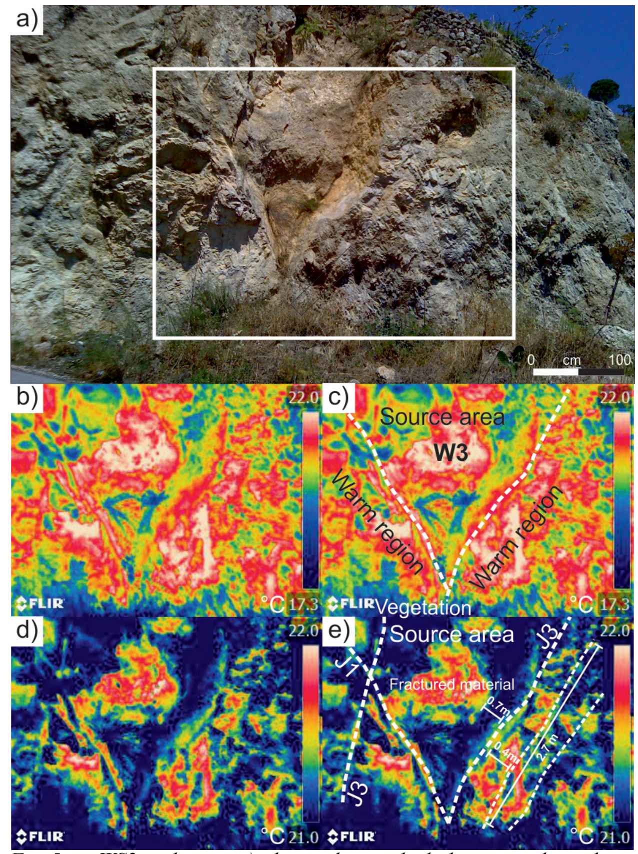

Fig. 5 - WS2 rock mass a) photo taken in daylight, rectangle encloses the area of thermograms; b) thermogram 17.3-22°C, c) thermogram 17.3-22°C with particular elements highlighted; d) thermogram 21-22°C; e) thermogram 21-22°C with particular elements highlighted

DISCUSSION AND CONCLUSIONS

InfraRed Thermography proved a valid technology for the survey of heavily jointed rock slopes, which show a predisposition to fail through wedge sliding. The surface temperature of a rock mass provides several information on the geomechanical condition of the slope, since the heat distribution is strongly influenced by discontinuity systems. In particular, thermal images acquired in nighttime highlighted relevant criticalities related to potentially unstable areas, involving also possible reactivation of previous events. If water circulation within the rock mass can be excluded, as in the case presented herein (no water surveyed during the in situ measurements), the highest temperatures are related to fractured/crushed sectors and to opened discontinuities, while the lowest values belong to smooth and low fractured surfaces. In this view, a mapping of the main discontinuity systems and of the most fractured sectors is feasible based on the analysis of thermograms. In this procedure, a digital elaboration of the image, aimed at isolating specific temperature ranges, is useful to highlight specific anomalies.

In the case study presented in this paper, two carbonate rock masses were surveyed through both geostructural surveys and IRT. Data retrieved during the direct survey were considered as reference values for the analysis of thermograms. In particular, at WS1 infrared images allowed identifying three main rock wedges occurring along the slope. These are characterized by well-defined contours belonging to relevant discontinuity systems. In this case, the great hint provided by IRT is the detection of intensely fractured rock, which is likely to have already been subject to local decompression phenomena. This appears as positive anomalies in the thermogram and represents potentially unstable material within the wedge area. In fact, heavily fractured/crushed rock is likely to be affected by very poor geomechanical properties and represents the ideal point for water infiltration during the rainy season. All these features are considered among the main causes of slope instability. Such considerations originates from the analysis of the surface temperature of the rock face, highlighting the relevance of IRT in this field.

Similar outcomes characterize WS2, where the mark of a source area of a previous rockfall is present next to an incipient, unstable rock wedge. In this case, IRT was aimed at analyzing the source area of the wedge and its surroundings, providing important information on the poor condition of the rock, especially around and within the source area itself. The analysis of thermal image allowed identifying potential enlargement sectors of the wedge, suggesting possible reactivation of the landslide and slope retreat phenomena. Furthermore, by scaling the thermogram and taking advantage from the depth of the source area, the volume of the unstable rock material was assessed. It represents a suitable reference value for a preliminary evaluation of the entity of potential failures, proving a further utility of IRT during such kind of survey.

Although further studies are needed for the validation of this technique at a larger scale, achieved results demonstrate the reliability of IRT during the stability analysis of rock slopes, especially if coupled with a geostructural survey. Its utility may bring a great help also for the extension of the survey to portions of the slope which are not directly reachable, such as higher sectors or coastal cliffs.

REFERENCES

Baroň I., Bečkovský D. & Míča L. (2012) - *Application of infrared thermography for mapping open fractures in deep-seated rockslides and unstable cliffs.* Landslides, **11**: 15-27. DOI 10.1007/s10346-012-0367-z.

Bieniawski Z.T. (1989) - *Engineering rock mass classification*. John Wiley & Son, New York.

Cirrincione R., Fazio E., Ortolano G., Pezzino A. & Punturo R. (2012) - *Fault-related rocks: deciphering the structural-metamorphic evolution of an accretionary wedge in a collisional belt, NE Sicily.* Int. Geol. Rev. **54** (8): 940-956. http://dx.doi.org/10.1080/ 00206814.2011.623022.

Ferrero A. M., Forlani G., Roncella R. & Voyat H.I. (2009) - *Advanced geostructural survey methods applied to rock mass characterization*. Rock Mech Rock Eng, 42, 631–665. DOI 10.1007/s00603-008-0010-4.

Finetti I., Lentini F., Carbone S., Catalano S. & Del Ben A. (1996) - *Il Sistema Appennino Meridionale-Arco Calabro-Sicilia nel Mediterraneo centrale: studio geologio-geofisico.* Boll Soc Geol It, **115**: 529-559.

Goodman R.E. (1989) - *Introduction to rock mechanics*. 2nd edn. Wiley, New York.

Hoek E. & Bray J.W. (1981) - R*ock Slope Engineering*. Third Edition, The Institution of Mining and Metallurgy, London, 368 pp.

Hudson R.D. (1969)- *Infrared System Engineering.* Wiley-Interscience, John Wiley & Sons, New York/London/Sydney/Toronto, 642 pp.

ISRM (2007) - *The complete ISRM suggested methods for rock characterization, testing and monitoring: 1974-2006.* In: Ulusay R. & Hudson J.A. (eds.). *Suggested methods prepared by the commission on testing methods*. International Society for Rock Mechanics, Compilation Arranged by the ISRM Turkish National Group, Kozan Ofset, Ankara, Turkey, 628 pp.

Jimenez-Rodriguez R. & Sitar N. (2007) - *Rock wedge stability analysis using system reliability methods.* Rock Mech. Rock Engng. **40** (4): 419-427.

Kovari K. & Fritz P. (1976) - *Stability analysis of rock slopes for plane and wedge failure with the aid of a programmable pocket calculator.* Rock Mechanics, **8** (2): 73-113.

Lentini F., Carbone S. & Guarnieri P. (2006) - *Collisional and postcollisional tectonics of the Apenninic-Maghrebian orogen (southern Italy).* Special Paper of the Geological Society of America, **409**: 57-81. DOI: 10.1130/2006.2409(04).

Low B. K. (1997) - *Reliability analysis of rock wedges.* J. Geotech. Geoenviron. Engng. **123** (6): 498-505.

Mineo S., Pappalardo G., Rapisarda F., Cubito A. & Di Maria G. (2015a) - *Integrated geostructural, seismic and infrared thermography surveys for the study of an unstable rock slope in the Peloritani Chain (NE Sicily).* Engineering Geology, **195**: 225-235. doi: 10.1016/j.enggeo.2015.06.010.

Mineo S., Calcaterra D., Perriello Zampelli S. & Pappalardo G. (2015b) - *Application of Infrared Thermography for the survey of intensely jointed rock slopes.* Rend. Online Soc. Geol. It., **35**: 212-215. doi: 10.3301/ROL.2015.103.

Palmström A. (2005) - *Measurements of and correlations between block size and Rock Quality Designation (RQD).* Tunnels and Underground Space Technology, **20**: 362-377.

Pappalardo G., Mineo S. & Rapisarda F. (2014) - *Rockfall hazard assessment along a road on the Peloritani Mountains (northeastern Sicily, Italy).* Natural Hazards and Earth System Sciences, **14**: 2735-2748. doi: 10.5194/nhess-14-2735-2014.

Pappalardo G. & Mineo S. (2015) - *Rockfall hazard and risk assessment: the promontory of the pre-hellenic village Castelmola Case, North-Eastern Sicily (Italy).* Engineering Geology for Society and Territory - Volume 2: Landslide Processes, 1989-1993. DOI: 10.1007/978-3-319-09057-3_353.

Shannon H.R., Sigda J.M., Van Dam R.L., Handrickx J.M.H. & Mclemore V.T. (2005) - *Thermal camera imaging of rock piles at the Questa Molybdenum Mine, Questa, New Mexico.* Proc. 2005 National Meeting of the American Society of Mining and Reclamation, June 19-23, 2005, ASMR, 1015-1028.

Teza G., Marcato G., Castelli E. & Galgaro A. (2012) - *IRTROCK: A MATLAB toolbox for contactless recognition of surface and shallow weakness of a rock cliff by infrared thermography.* Computers & Geosciences, **45**: 109-118.

Trombetta A., Cirrincione R., Corfu F., Mazzoleni P. & Pezzino A. (2004)- *Mid-Ordovician U-Pb ages of phorphyroids in the Peloritani Mountains (NE Sicily): paleogeographical implications for the evolution of the Alboran microplate*. J. of the Geol. Soc. London, **161**: 265-276.

Wang Y.J. & Yin J.H. (2002) - *Wedge stability analysis considering dilatancy of discontinuities*. Rock Mech. Rock Engng. **35** (2): 127-137.

Warburton P. M. (1981) - *Vector stability analysis of an arbitrary polyhedral rock block with any number of free faces*. Int. J. Rock Mech. Min. Sci. **18** (5): 415-427.

Wu J.H., Lin H.M., Lee D.H. & Fang S.C. (2005) - *Integrity assessment of rock mass behind the shotcreted slope using thermography.* Engineering Geology, **80**: 164-173.

Received November 2015 - Accepted May 2016