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THE SAN LEO CLIFF IN THE NORTHERN APENNINES, ITALY: SLOPE INSTABILITY AND RISK MITIGATION MEASURES AFTER THE 2014 LANDSLIDE

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EXTENDED ABSTRACT

L'abitato di San Leo, nel cuore della valle del Marecchia (Rimini, Emilia-Romagna), con la sua storica fortezza sorge su una rupe isolata e circondata da terreni argillosi come gran parte dei borghi storici medioevali dell'Italia (es. Orvieto, Civita di Bagnoregio) che hanno dovuto fare i conti da sempre con il dissesto idrogeologico. Esistono testimonianze storiche che mostrano una rupe di San Leo diversa e ben più estesa rispetto ad oggi: secoli di frane l'hanno progressivamente ridotta così come la vediamo oggi.

L'ultimo crollo in ordine di tempo, avvenuto nel febbraio 2014, si aggiunge alla lunga serie di fenomeni franosi che continuano a minacciare l'integrità dell'ammasso roccioso e con esso la sicurezza della città di San Leo, fortezza compresa.

San Leo è stato dichiarato "abitato da consolidare" ai sensi della L. 445/1908 con D.P.R. 217 del 18 gennaio 1951. Dal 2004, con adozione del Piano Stralcio per l'Assetto Idrogeologico (PAI) Marecchia-Conca, tutta la fascia di territorio attorno alla rupe di San Leo è perimetrata, ai sensi della L. 267/1998, come area a rischio idrogeologico molto elevato.

Negli ultimi settant'anni sono stati eseguiti diversi interventi di consolidamento delle pareti rocciose, in particolare lungo la parete sud, sede dell'abitato e della via di accesso all'abitato stesso e lungo la parete est, nel settore occupato dalla fortezza. A partire dagli anni Ottanta, gli interventi per la mitigazione del rischio hanno riguardato anche le aree ai piedi della rupe, con l'intento di ridurre l'azione erosiva dei fossi Campone e Seripa e impedire lo scalzamento alla base della rupe, che è stato all'origine dei grandi crolli come in occasione della frana del 2014. Nonostante gli interventi eseguiti nel passato, più o meno recente, che pure hanno rappresentato tappe importanti nel difficile percorso di contrasto al dissesto da frana, il grado di rischio idrogeologico che caratterizza la rupe di San Leo rimane ancora elevato.

Con il crollo del 2014, la Rupe di San Leo è stata oggetto di un approfondito studio multidisciplinare che ha visto l'impiego di diverse tecniche di indagine e di monitoraggio per la prevenzione e la mitigazione del rischio idrogeologico. L'approfondimento conoscitivo è stato fondamentale nella gestione dell'emergenza all'indomani del crollo, fornendo gli elementi necessari per la definizione degli scenari di rischio e la formulazione del piano di emergenza di protezione civile. In particolare, durante la fase emergenziale, è stato installato un sistema di monitoraggio che, per come è stato concepito e strutturato, può essere ritenuto a tutti gli effetti un intervento non strutturale di mitigazione del rischio idrogeologico. Rappresenta di fatto unico elemento di presidio nell'area attorno al crollo dal momento che non è stato possibile attuare interventi di consolidamento direttamente sulla parete di frana per ragioni di sicurezza.

Le stesse informazioni acquisite durante la fase emergenziale, integrate con ulteriori approfondimenti specifici, sono risultate indispensabili per la programmazione e la progettazione degli interventi post-emergenziali di mitigazione del rischio, alcuni dei quali già realizzati, altri in fase di realizzazione e di progettazione.

Il crollo del febbraio 2014 ha riproposto con forza il problema della sottoescavazione delle argilliti e, in generale, della stabilità dell'area del fosso Campone, accrescendo la convinzione che per limitare/impedire il propagarsi dei grandi crolli sarà necessario eliminare l'erosione delle argille ai piedi della rupe. Pertanto, sono stati avviati (e conclusi) i primi interventi strutturali per trattenere la coltre detritica addossata alla parete e proteggere, in questo modo, le argille dall'erosione e da potenziali fenomeni franosi.

Una seconda priorità di intervento, emersa all'indomani del crollo 2014, è rappresentata dalla pericolosità della strada di accesso alla fortezza che passa a pochi metri dal ciglio della parete est. Per mitigare il rischio è stato realizzato un intervento di consolidamento del tratto di parete ritenuto pericoloso attraverso l'impiego di barre in acciaio (ancoraggi passivi) inserite in profondità all'interno dell'ammasso.

Dopo i primi interventi realizzati per la mitigazione del rischio delle pareti nord ed est, l'attenzione è stata rivolta anche al versante sud, senz'altro il più critico in termini di esposizione al rischio e vulnerabilità. Un'accurata valutazione della pericolosità della parete sud ha indotto a ritenere indispensabile eseguire interventi di consolidamento anche su questo fronte. Un primo intervento, in corso d'opera, riguarda la porzione di parete in aggetto sotto l'abitato di San Leo, mentre un secondo intervento, in attesa di finanziamento, prevede il consolidamento della porzione di parete denominata il "canalone" e il rafforzamento corticale della porzione di parete immediatamente sotto la fortezza, a difesa dell'unica via di accesso all'abitato.

ABSTRACT

The medieval town of San Leo and its fortress have been classified as a “settlement to be consolidated”, following the Italian law. They rise on a rocky, steep cliff that is prone to failure, as well as the entire area surrounding the cliff is subject to slope instability phenomena. Over the past seventy years, a series of consolidation works have been conducted on the rock walls. These interventions focused mainly on the south face, where the town and its access road are located, and on the east face, particularly in the area where the fortress is situated. Since the 1980s, efforts to reduce the risk have also focused on the base of the cliff with the aim to prevent its erosion and undermining. The latter is considered the cause of major rock failures, such as the landslide that occurred in 2014. Despite past interventions, however, landslide risk in the San Leo cliff still remains high. The slope failure of 2014 marks a dividing line: after that a comprehensive multidisciplinary study was started. The study involved different investigation and monitoring techniques in order to understand, prevent, and reduce landslide risk. The in-depth knowledge gained through this study was crucial in managing the emergency after the collapse, providing the essential elements for defining risk scenarios and for planning and designing interventions to reduce risk after the emergency phase. These interventions were carried out on the north face of the cliff, where the main landslide occurred in 2014, but also the east and south faces.

***Keywords**: San Leo, rocky cliff, slope instability, landslide risk, risk mitigation.*

INTRODUCTION

The medieval town of San Leo and its historic fortress stand on an isolated rocky cliff (the so-called “Rupe di San Leo”) surrounded by clayey slopes in the heart of the Marecchia valley, which is a significant part of one of the main tourist destinations of the Emilia-Romagna region, the Rimini district, in Italy. The area where the town of San Leo is located has a historical reputation for experiencing several significant landslide events, some of which were quite destructive. These events have been documented in historical records or inferred from ancient artistic depictions that illustrate a San Leo cliff larger than and different from what we see today (Benedetti *et alii*, 2013; Nesci & Guerra, 2013). The peculiar geological setting as well as its geomorphological features are responsible for the protracted, disastrous landslide phenomena affecting San Leo, like many other historic medieval villages in Italy, including the well-known examples of Orvieto, Civita di Bagnoregio, and Todi.

After several collapses that damaged the fortress and the access road to the town between 1930 and 1949, San Leo took the official designation of “town in need of consolidation” following the issuance of Presidential Decree 217 on 18 January 1951, in accordance with Law 445/1908. Since 2004, following the implementation of the “Extract Plan for the Hydrogeological Structure” (PAI) for the Marecchia-Conca district (now part of the Po River District Authority), the entire area surrounding the San Leo cliff has been designated as a zone at high hydrogeological risk, in accordance with Law 267/1998.

To confirm the level of attention that San Leo has garnered, also because of its relevant historical and touristic significance, several legislative proposals have been suggested in the past to safeguard and protect the town and the fortress. However, these proposals have never been fully processed. To reduce the risk, various consolidation interventions have been conducted on the rock faces over the past seventy years. These interventions have focused mainly on the south face, where the town and its access road are located, and on the east face, particularly in the area where the fortress is situated. At the end of the 1970s, interventions for risk mitigation also included the areas at the base of the cliff, in order to decrease the erosive impact of the Campone and Seripa streams and to prevent the under-excavation at the cliff’s base, which led to significant failures like the 2014 landslide. Despite the interventions carried out in the recent past, the level of hydrogeological risk for the San Leo village still remains high.

The large landslide occurred in February 2014 represents a new fact in the risk management of the entire San Leo cliff, since before this event the northern slope was not considered an area at risk in the same way as the southern (the village and its access route) and eastern slope (fortress and its access road). On the northern slope, only the water treatment plant and, marginally, the San Leo ring road were considered potentially at risk. However, since the 2014 landslide caused the edge of the cliff to retreat so much as to come close to civilian homes, the north side also gained a reputation as high-risk and highly vulnerable area.

After the initial risk reduction measures implemented in alternating phases between 1949 and 2008, following the collapse in 2014, the San Leo cliff underwent a comprehensive multidisciplinary study through various investigative techniques and monitoring methods to prevent and mitigate hydrogeological risks. This in-depth knowledge was fundamental in managing the emergency providing the essential elements for defining risk scenarios and formulating the civil protection emergency plan. Furthermore, it has been possible to define a geological model of the cliff, recognizing the main discontinuity systems, and tracing the causes of the instability and the movement of the rock masses. The knowledge acquired so far is essential for planning and designing further risk mitigation interventions. Some of these interventions have already been completed, while others are in progress.

This review paper aims to explain the intervention strategy used after the collapse, during the emergency, and afterwards. It also describes the specific actions undertaken to address slope instability issues.

GEOLOGICAL SETTING

The “Rupe di San Leo” is situated in a large area of Montefeltro where the well-known “Coltre della Val Marecchia” (Ruggeri, 1958) crops out, consisting of geological units belonging to the two paleogeographic domains, the Ligurian and Epiligurian realms (Fig. 1). It is a tectonic and/or gravitational allochthonous nappe that was emplaced during the formation of the Apennine chain, overlying the Umbria-Marche-Romagna succession (*e.g.* Ricci Lucchi, Ori, 1985; De Feyter, 1991; Conti, 1994; Conti & Tosatti, 1996; Roveri *et alii*, 1999; Lucente *et alii*, 2002).

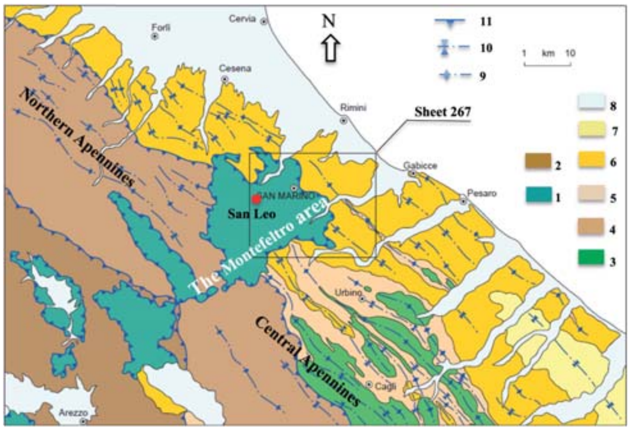

Fig. 1 - Schematic geological map of the Montefeltro area between the Northern and Central Apennines (from the Geologic Map, scale 1:50.000 - Sheet 267 “San Marino”, modified). Legend: 1 - Ligurian and epi-Ligurian units (Coltre della Val Marecchia); 2 - Tuscan units; 3 – Jurassic-Miocene, calcareous- marly succession (Umbria-Marche foreland units); 4 – Siliciclastic succession of the Miocene, Umbria-Romagna and Marche foredeep units; 5 – Siliciclastic succession of the Umbria and Marche foredeep units (minor basins); 6 – Messinian-Pliocene succession; 7 – Quaternary marine deposits; 8 – Quaternary continental deposits; 9 – anticlines; 10 – synclines; 11 – overthrusts

The Ligurian units in the San Leo area consist mainly of clayey, marly and silty rock-units. These units have been significantly deformed by tectonic strain during the Apennine orogeny, often displaying the characters of broken formations with a distinct scaly fabric of the predominant clayey component (known as “Argille Scagliose” in the Italian geological literature). The Epiligurian succession lies above the Ligurian units, separated by a significant regional stratigraphic discordance (Ricci Lucchi, 1986). The deposition of the stratigraphic terms of this succession always took place on top the Ligurian nappe, as it moved north-eastward, leading to its current geographical position (Fig. 1).

The San Leo cliff has a rectangular shape and is defined by steep, nearly vertical walls that jut out, reaching heights of up to 100 meters. It is composed of rocks from the Epiligurian units, belonging to the San Marino Formation, which consists mainly of biocalcarenites and hybrid calcarenites, and the Monte Fumaiolo Formation, which consists mainly of bioturbated and fossiliferous sandy marls interbedded with mixed-hybrid sandstones (Fig. 2). The San Marino Formation crops out essentially in the northeastern part of the plate, characterizing the eastern and northern face of the cliff. Instead, the Monte Fumaiolo Formation, occupies the southwestern part of the plate, mainly constituting the western and southern sides of the cliff (Lucente, 2014; for more details see Landuzzi *et alii*, 2018 and this volume). The entire cliff is affected by an intricate system of faults and pervasive fractures making the rock mass particularly susceptible to landslides. The clayey substrate on which the cliff rests belong to the Varicolored Clays, which are an intensely deformed up to disrupted rock unit (broken formations), characterized by a typical scaly fabric. This geological setting favours selective erosion giving rise to rigid rocky plates that “float” on softer, more erodible clayey rocks. This also impact on typical landscape of the Marecchia Valley, with rocky cliffs (Epiligurian successions) standing on gently slopes or badlands (Ligurian units). In the case of the San Leo cliff, the erosion affecting the Varicolored Clays is intensified by the water action along the two streams, Seripa and Campone, which, encircling the rocky plate, have increased the steepness of the slopes. The Campone stream is currently experiencing

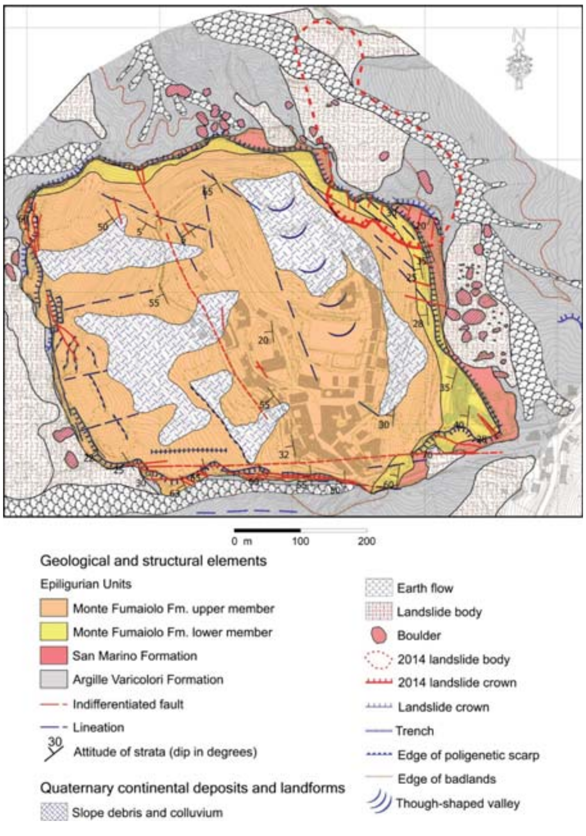

Fig. 2 - Geologic map of the San Leo cliff (after Borgatti et alii, 2015)

significant imbalance, leading to pronounced erosion and a gradual deepening of the base level. This plays a crucial role in the area's morphological changes and contributes to slope instability at the cliff's base. (Fig. 3).

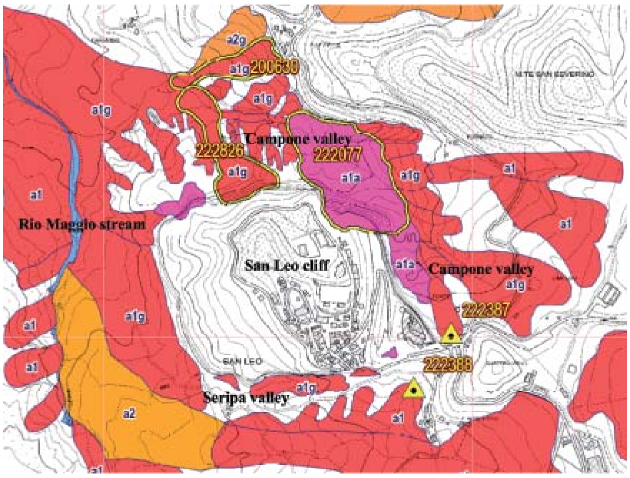

Fig. 3 - Active landslide deposits surrounding the San Leo cliff, along the Campone and Seripa valleys (from the landslide inventory map of the Emilia-Romagna Region, modified). The Campone and the Seripa streams flow into the "Rio Maggio" stream. Legend: a1=indeterminate active landslide deposit, a1a=rock fall active deposit, a1g= complex active landslide, a2=indeterminate dormant landslide deposit, a2g=complex dormant landslide deposit

HISTORICAL SLOPE INSTABILITY AND THE 2014 LANDSLIDE

Due to the geological and geomorphological context in which it is located, the Rupe di San Leo shows a strong tendency toward slope instability. On the entire perimeter of the cliff there are signs of landslides of various sizes ranging from the simple detachment of small portions of overhanging rock to the collapse of large rock masses resulting in the retreat of the front (Benedetti *et alii*, 2013).

Even recently the north side of the cliff has been affected by large landslides. The 2006 event generated the failure of approximately 50,000 m^3 of rock, causing damage to the sewerage and treatment plant serving the city of San Leo (Fig. 4).

Even more impressive was the 2014 event which affected a large portion of the rock mass equal to a volume of 330,000 m^3, along a front approximately 160 m wide and approximately 100 m high (Fig. 4). The scarp showed a retrogression of about 30 m. Following the failure of the rock mass, the debris propagated (block and debris avalanche) violently along the Campone valley for 400 metres, raising a gigantic cloud of dust and projecting blocks of rock for hundreds of metres. The landslide debris covered an area of 60,000 m^2 with huge boulders up to 10.000 m^3 (Lucente, 2014; Borgatti *et alii*, 2015). In the days following the event, the largest amount of debris near the wall was found to be stable, except for some boulders that moved at a speed up to 30 cm/day. At the toe of the debris, along the axis of the Campone valley, an earth slide/flow was recorded. This earth movement, similar to what was observed in the 2006 event, occurred immediately after the catastrophic failure due to a mechanism of undrained loading.

Also, on the eastern and southern sides there is historical evidence of rockfall. Large landslides occurred in the recent past, from 1930 to 1962 (Lembo-Fazio *et alii*, 1998), at the southeastern corner of the cliff involving parts of the fortress. This led to a temporary isolation of the town due to the interruption of the only access road. Several events are also documented in the sector below the access door to the town, leading to an overhanging of over 10 meters. Among other items, landslides destroyed the ancient access road to the town ascending from the Seripa stream ("*Porta di Sopra*") along a winding path with historical arched structures, the remnants of which are still visible. The eastern wall under the fortress has also been the subject of several failures in the past. The large accumulation at the base of the wall with giant boulders suggests that the eastern slope also underwent undermining phenomena (Fig. 4). The entire cliff is intensely fractured, with multiple fracture systems. These fractures are a result of tectonic and gravitational processes, both fossil and recent, experienced during its complex geological history. The contrast in rigidity between the calcareous and calcarenitic rocky plate and the clayey substrate leads to a complex state of stress in the cliff, causing fractures to gradually open along the edges of the plateau, roughly parallel to the walls. Large cavities develop at the contact between the rocky plateau and the Varicolored Clays due to slides and flows even because of the erosion of the Campone and Seripa streams on the clayey substrate. This undermining at the base of the cliff lead to large slope failures. This is what happened with the recent rock fall in 2014 along the northern slope of the San Leo cliff (Fig. 4).

The kinematics of these large landslide may be connected to deep-seated gravitational slope deformations, influenced by the high lithostatic pressure of the rocky plateau on the clays (Cancelli & Pellegrini, 1987). This could lead to uneven settling in the rock mass, accompanied by fluidification of the saturated clays, with plastic behaviour, towards the external areas of the rocky plateau, also causing swelling at the base of the cliff.

The geomorphological evolution of the cliff and the surrounding slopes is therefore conditioned by the cause-effect interactions between the rigid rock mass and the plastic clays. For large-scale landslide, like the one in 2014, the causes can be linked to: 1. water seeping into open fractures leading to changes in the discontinuity surfaces and the development of pseudo-karst landforms, as well as increase in the opening of the fractures themselves; 2. remoulding of the clays occur,

Fig. 4 - Panoramic photo from helicopter after the 2014 event at the north-east edge of the cliff. The landslide generated an extensive and thick rock avalanche deposit invading the Campone valley. On the right, along the north side of the cliff, we can appreciate the 2006 rock-fall deposit at the foot of the wall. Finally, an ancient huge landslide rests at the foot of the east face

particularly towards the plate's edges where there is minimal lateral confinement, and where the groundwater held by the fractured aquifer within the calcarenites tends to concentrate and flow; 3. saturation of the basal clays with chemical and physical-mechanical alteration leading to a gradual reduction in the shear resistance; 4. undermining of the steep fractured rock walls due to the systematic mobilization of the basal clays and predisposition to topple/fall (Ribacchi & Tommasi, 1988; Lucente, 2014; Borgatti *et alii,* 2015) (Fig. 5).

The reduction of the geotechnical parameters of the clays under the cliff and the removal of portions of clayey substrate at the edges are widely observed phenomena and probably act concomitantly. With the removal of the uppermost layer of the clays, even the innermost and deeper materials can undergo weathering phenomena, and this leads to the progressive widening of the cavities under the cliff. It should be noted that before the February 2014 collapse, cavities up to 20 meters deep were verified (Fig. 5).

In the proposed model, priority is given to the effect of undermining which determines the opening of vertical fractures parallel to the rock face and subsidence and rotation of marginal blocks. However, the importance of the clay squeezing at the base of the walls cannot be excluded. To reproduce the observed failure mechanism, however, the presence of subvertical fractures at the top of the cliff's wall is crucial. The opening of these fractures, as previously noted, is promoted by the tensile stress caused by the interaction between the rock plate and

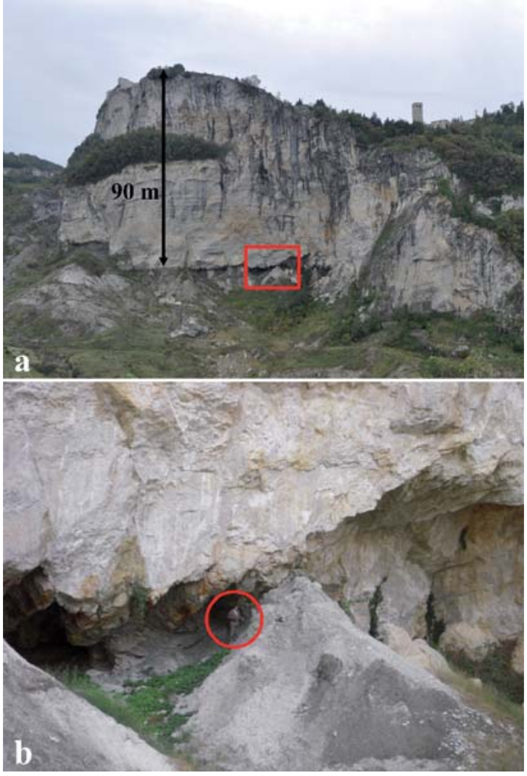

Fig. 5 - a) The undermined north face of the San Leo cliff before the 2014 landslide; b) the detail shows the size of undermining (man as a scale, red circle)

the clay substrate. This is what clearly emerges from the back analysis of the 2014 landslide and from the numerical modelling of the factors predisposing to the collapse (Spreafico *et alii*, 2016; Spreafico *et alii*, 2017; Donati *et alii*, 2019; Donati *et alii*, 2021; Donati *et alii*, 2023).

Apart from the large-scale rockfall-toppling phenomena involving the entire thickness of the cliff, there are minor rock falls affecting only a part of the rock face. They occur by rock blocks detachment along basal fracture planes and by collapses and/or toppling of vertical rock. This type of failure occurs widely along the entire perimeter of the San Leo cliff. Finally, where there are portions of intensely fractured rock, generalized collapses of the most superficial and altered blocks can be observed.

RISK MITIGATION MEASURES AFTER THE 2014 FAILURE

There have been several interventions in San Leo to reduce landslide risks and to remedy the risk-related damages in recent decades. It began with building a viaduct after the collapse in 1949, which affected a significant part of the southeast corner of the cliff below the fortress. This was done to prevent the interruption of the town's sole access road.

Since then, various interventions have taken place over time to consolidate the rock walls and to arrange and stabilize the clay slopes surrounding the cliff (Ribacchi, 1987; Ribacchi & Tommasi, 1988; Caturani *et alii*, 1991; Lucente, 2019 and references therein). The various interventions were preceded and accompanied by surveys and investigations. Over the years, monitoring has been initiated, although not consistently, to manage landslides and confirm the efficiency of the interventions implemented. With few exceptions, the interventions can essentially be traced back to three distinct periods, the start of which is systematically linked to significant landslide events that have drawn attention to the risk and the awareness of remedying it. A first phase developed between 1969 and 1988, a second phase between 1999 and 2008 and a third phase, still ongoing, started after the 2014 collapse.

The emergency phase

After the disastrous landslide of 2014, following initial post-emergency assessments and the identification of a large area a risk, a comprehensive and interdisciplinary study was initiated. This study was essential for comprehending the landslide event by defining the volume the failure mass, the width of the affected area, the reasons behind the event, and the geomechanical condition of the fractured rock mass. The information and data acquired were used to:

1) plan and implement a monitoring system for controlling the main fractures (master joints) in the rocks around the failure area, in order to protect the access road to the fortress and the part of settlement extending on the northern side of the rocky cliff;
2) carry out stability analyses on the rock mass;
3) define a more precise risk scenario, which has been updated as the studies progressed;
4) plan and start the initial structural interventions in the unstable area based on a prioritized order, considering the level of risk exposure and vulnerability of the affected areas.

\- *Terrestrial Laser Scanner Survey*

The first step was a survey of the 2014 landslide scarp with a terrestrial laser scanner, generating a georeferenced point cloud (in the WGS84 reference system) with respect to two distinct observation points, acquiring the collapse front with a high resolution. In this way it was possible to obtain the new morphology of the rock face in detail through three-dimensional modelling. The data obtained from the post-landslide laser scanner survey was then compared with a survey carried out before the collapse, in 2011 (Territorial Office of Rimini -Regional Agency for territorial security and civil protection), allowing the volumes of rock involved in the collapse to be calculated rather precisely.

The use of the laser scanner survey was not limited to the morphological evaluation of the rock wall alone, but the interpolated position of the fracture planes was also obtained, the analysis of which was performed with the aid of the COLTOP 3D software (Spreafico *et alii*, 2015). Essentially five families of fractures were detected, confirming the same systems detected through traditional geomechanical survey both on the wall and on the top of the cliff (see paragraph "Geomechanical survey").

\- *Photogrammetric Survey*

The use of the drone (UAV - Unmanned Aerial Vehicle) was dictated by a dual need: 1) to check the state of stability of the rock wall to allow rock-climbing geologists to carry out the inspection and geomechanical survey in safety and 2) to obtain the three-dimensional model (DTM - Digital Terrain Model) of the San Leo rocky cliff and the surrounding area in a short time.

To verify the safety level of the wall, full HD videos were produced which allowed to analyse in detail the fractures present on the front of the collapse. The detailed images of the fractures were used for the geomechanical assessment of the fracture network, integrating the analyses on the top of the cliff and the direct checks on the wall (see paragraph "Geomechanical survey").

\- *Geomechanical Survey*

The main goal of the geomechanical survey in the area of the 2014 landslide was to define the primary families of fractures that characterize the rock mass. This was achieved through two different approaches: one focuses on measuring the fractures that are visible at the top of the cliff, while the other involves directly measuring the fractures on the wall using mountaineering techniques. The geomechanical survey of the state of fracture on the top extended to the entire northeastern portion of the San Leo cliff, around the scarp, coinciding with the area at major risk identified immediately after the collapse.

The geo-mechanical survey at the summit revealed the existence of four main sets of fractures known as K1, K2, K3, and K4, along with another set of discontinuities corresponding to the stratigraphic (bedding) surfaces, called Ks. Two other smaller fracture sets, K0 and K5, were also identified (Fig. 6).

In short, the K1 family identifies a system of normal faults with high dip angle. The K2 family identifies fractures associated with the main San Leo fault system, always at a high dip angle. The K3 family identifies fractures striking at approximately 70° with the K1 family and always at a high angle of inclination.

Fig. 6 - a) Trace of the main fractures on the top of the cliff (families K1, K2, K3 and K4); b) and c) details of the K3.2 fracture which belongs to the same family as the fracture of the 2014 landslide

This family comprises two very distinct individual fractures, called K3.1 and K3.2, open several centimetres and probably quite persistent, similarly to the fracture that generated the scarp of the event of February 2014. The K4 family is approximately parallel in strike to the K1 family but shows a variable inclination between 30 and 60 degrees.

The wall survey was carried out with mountaineering technique (rope abseiling) with the dual purpose of closely observing the large fracture systems identified by frontal visual inspection by drone and of following the continuity of the large fracture systems found on the summit. Wall inspections does not claim to be a thorough investigation of discontinuities, but rather aims to observe the peculiar characteristics of the joints, such as opening, filling conditions, possible signs of recent movements, humidity and any sign of water circulation. Furthermore, it is worth specifying that the investigations were aimed at inspecting the most pervasive fractures, which can potentially cause collapses of relatively large volumes, while less weight was given to localized and/or surficial failures, less important in the emergency phase. Figure 7 shows, respectively for the northern face and the eastern face, the main fractures detected through the descents of the rock-climbing geologists. The mutual crossing of the main fractures (master joints) obtained allowed us to schematically identify the main blocks into which the rock in the neighbouring of the detachment surface of 2014 collapse can be divided, for the purposes of stability analyses.

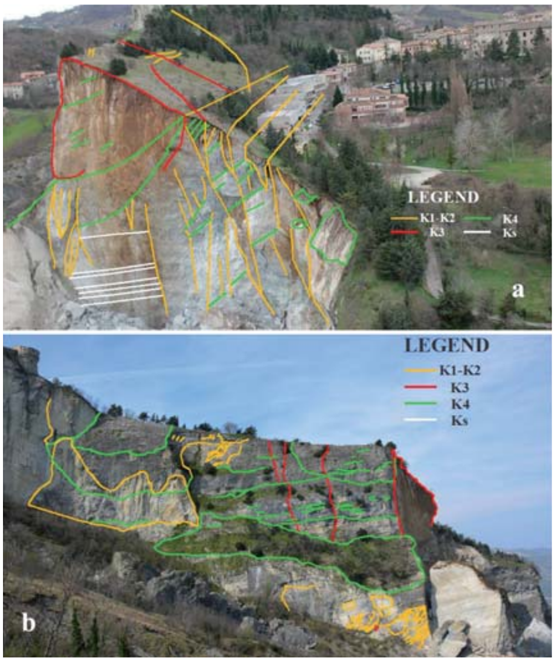

Fig. 7 - a) Main fractures detected along the scarp (north wall); b) main fractures detected along the east wall

- *Core Drilling*

Along the access road to the fortress at the hairpin turns, which after the first surveys was found to be a rather critical area in terms of safety, a vertical borehole has been drilled for an in-depth verification of the state of fractures in the rock mass to integrate geomechanical surveys carried out on the outcrops. The investigation was completed with a video and acoustic survey inside the hole. The analysis of the core and the video inspection images provided interesting and very detailed information on the deep cracking state (discontinuities and alteration bands).

Eight continuous core drillings with depths varying between 20 m and 70 m and with an inclination to the horizontal plane varying between 5° and 30° have also been carried out. In addition to serving for the installation of the borehole extensometers along the crown of the 2014 landslide event, they provided further, important indications on the conditions of the rock mass in the vicinity of the crown of the landslide, both through the analysis of the cores and through video inspection.

- *Monitoring System*

Immediately after the 2014 event, a ground-based SAR was installed opposite to the north-eastern sector for real time control of the residual movement of both the rock wall scar and the rock fall deposits (Frodella *et alii*, 2016). Then an integrated monitoring system was installed to control the main fractures (master joints) as identified by geomechanical field survey (Lucente, 2014; Borgatti *et alii*, 2015; Borgatti & Lucente, 2018). It is made up of multipoint borehole rod extensometers, for checking fractures in depth, and wire crackmeters and jointmeters, for checking fractures on the surface (Fig. 8).

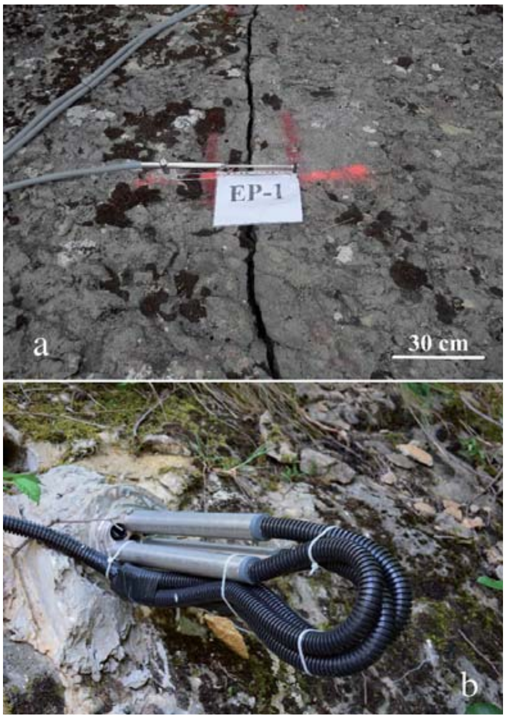

Fig. 8 - a) Jointmeters and b) multipoint borehole extensometer

Some fractures are monitored by multiple instruments in order to have more data collected for the same fracture. The monitoring of fractures started in April 2014, and it is still working. The San Leo monitoring system was conceived with a two-folds function, concerning both *i*) study and knowledge and *ii*) alert/alarm.

The study function consists in providing information on the stability of the rock mass, on the ongoing failure mechanisms and on the possible evolution of the risk scenario. Furthermore, the interpretation of the data supports interventions to consolidate the rock mass and mitigate landslide risk. This involves periodically analysing the data acquired by the control units and transmitted to the dedicated website. The processing involves the analysis of historical series to verify and interpret the behaviour of fractures over time and following external events such as earthquakes or adverse weather conditions.

The alarm function is based on pre-established movement thresholds. When they are exceeded, the alarm system automatically sends SMS messages to the emergency network address book defined in the "Rupe di San Leo" emergency plan. Today, the alarm function is suspended after almost 10 years of activity.

The monitoring system can be seen as a non-structural intervention that works alongside hydrogeological risk. In fact, it protects a large section of the cliff that is at risk, allowing people to live acknowledging the danger, particularly in cases where structural reinforcement is not feasible.

- *Stability Analysis*

The geomechanical data were used for stability assessment as an additional factor in decision-making when assessing and defining risk scenarios. The following are the result of the stability analysis for the different parts of the cliff.

- *Global stability analysis of the collapsed wall (northern wall)*

The global stability analysis of the northern face was conducted using finite element (Fem; Carlomagno, 2014a) and distinct element (Dem; Doglioni *et alii*, 2014a) methods. The verification methods show that the cause of global instability of the wall is the undermining at the base of the rocky plate. This phenomenon, crucial in triggering large-scale collapses, seems to be on hold as the clays at the base are now covered by the debris created during the event on 27 February 2014 and, as such, are not further subject to erosion and remobilization. In the long term, after the erosion of the debris deposit, the afore-mentioned unfavourable conditions that still exist will reactivate erosive processes at the cliff base.

- *Local stability analysis of the collapsed wall (north wall)*

The local stability analyses of the north face were conducted using the limit equilibrium method (Boldini & Tommasi, 2014a; Doglioni *et alii*, 2014a). The analysis focused on the central portion of the collapse, a highly fractured area by joints K1 and K4 (Fig. 9). The stability analyses of the rock wedges meet the static requirements, but there are still uncertainty factors that make the edge unsafe. Regarding the stability of the area, it seems to be in a precarious state because of the potential sliding of rock blocks along the discontinuities of the K4 family.

- *Stability analyses of the east wall*

The stability analyses of the east wall were conducted with the limit equilibrium method (Boldini & Tommasi, 2014b), the finite element method (Carlomagno, 2014b), and the distinct element method (Doglioni *et alii*, 2014b). The local analysis was focused on a large rocky slab below the access road to the fortress of San Leo. The sliding of this rocky slab could disrupt road traffic and jeopardize the safety of vehicles and people passing through. It should be noted that the investigations reasonably allow us to believe that the collapse which occurred on 27 February 2014 did not produce significant and visible damage in this area. The stability of the slab is therefore not substantially modified following the recent events. The most likely failure mechanism involves planar sliding along the discontinuities of the K4 family, dipping towards the outside of the rocky wall (see Fig. 7).

The stability analyses conducted led to the conclusion that the stability criteria are met only when assuming a certain percentage of rock bridges along the fractures of the K4 family. Unfortunately, determining the percentage of rock bridges on site with reliable precision is unlikely.

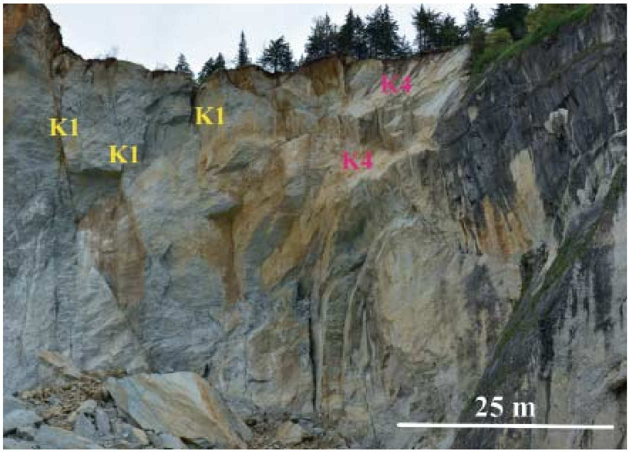

Fig. 9 - The highly fractured detachment scar in the north face, characterised mainly by K1 and K4 discontinuities

- *Risk Scenarios*

Taking to account the possibility of further failures, an assessment of the hazard and risk was made. As a precaution, the potential impact on a significant area surrounding the crown of the rock fall was evaluated (highlighted as the red area in Fig. 10a; the "risk scenario 1") including 5 buildings: a private cottage, two residential condominiums, the military police station ("Carabinieri") and the nursery-primary school (Fig. 10b). Obviously, the area at the foot of the scarp which includes all the landslide accumulation was also considered at risk.

The ban on access to the area led to the evacuation of 15 people and the moving of the activities and the personnel of school and Carabinieri to another locations.

The first surveys conducted, along with the use of interferometric radar (ground-based SAR) and the initiation of instrumental monitoring (to control surface fractures), allowed for an update of the initial risk assessment. With the new scenario, known as "risk scenario 2", the area around the collapse was divided into 4 zones: zone A, B1, B2 and C (Fig. 10c).

Zone A. The ring road was considered no longer safe due to a section of about 100 meters being close to the edge of the rock face and affected by significant fractures and discontinuity planes in the rock lying dip slope. It was therefore proposed to create an alternative route away from the edge and the potentially unstable area.

Zone B1. The private cottage, near the edge of the escarpment, and Condominium 1 are in an area currently classified as very high risk. Therefore, it was decided to keep the restriction on their use until the study and monitoring system are finished. After completion, the risk status of both buildings and their usability will be reassessed.

Zone C. The police station, condominium 2, and the school seemed to be in a lower-risk area, away from the areas that might be affected by a further landslide. It was therefore considered possible to remove the restrictions under the following conditions: activation of phase 1 monitoring and definition of the related Civil Protection Emergency Plan.

Zone B2. The studies conducted have highlighted that the hairpin turn area of the access road to the fortress is not among the areas affected by the failure of February 2014, nor are there any visible or tangible damages attributable to the failure. However, the initial surveys of the wall revealed a risky situation due to

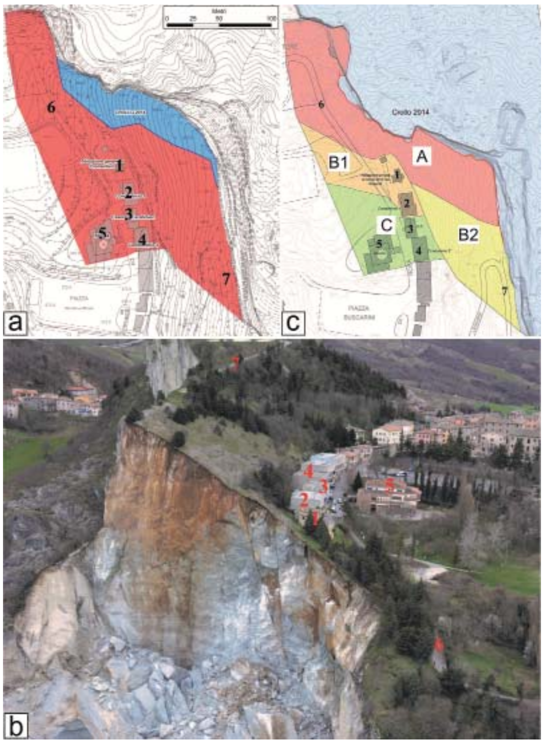

Fig. 10 - a) The first risk scenario defined immediately after the 2014 landslide; b) the photograph shows the elements at risk falling into the red area. Legend: 1 – private cottage; 2 – residential condominium n.1; 3 – police station "Carabinieri"; 4 – residential condominium n.2; 5 – nursery and primary school; 6 – ring road; 7 – access road to the fortress; c) the last updated risk scenario – meaning of the four zones A, B1, B2, and C is explained in the text

the road's proximity to the edge of the slope and the presence of notable fractures. Regarding the reopening of the road, it was therefore considered essential to carry out further investigations.

The deep, vertical core drilling and the installation of strain gauges in the hole in the hairpin turn area (deep fracture control, July 2014) and the results of the first stability analyses made it possible to update the second risk scenario. This update, which resulted in defining "risk scenario 3," did not include a cartographic change but only modified the constraints within the B2 zone, specifically concerning the access route to the fortress. The update allowed access to the fortress to be reopened using an authorized shuttle with a limited number of trips, while the unsuitability for use of the private cottage and the condominium 2 was definitively confirmed.

Stabilization of the Campone area

The landslide of February 2014 highlighted the issue of undermining of the clays and the overall stability of the Campone gully. This emphasized the need to address weathering, erosion and clays remoulding at the base of the cliff to prevent the occurrence of further, large failures involving the entire rock mass.

Therefore, as part of the planning for the 2014 post-event interventions, the need to intervene maintaining the debris deposit against the wall to protect the clays from erosion and potential landslides was evaluated. However, it is evident that preventing the weathering and remoulding of the clays can be improved by draining the water away from the boundary between the rocky cliff and the underlying clays.

As a first step towards stabilizing the debris deposit and, in general, the entire area, two structural retaining works and deep drainage trenches were made. The planning of the interventions was based on data from previous geotechnical investigation and monitoring activity (2006 and 2015). The position of the two retaining works along the central axis of the Campone valley are shown in Figure 11a.

The initial task was to address the downstream movement observed in the basal clays at the toe of the debris deposit, shortly after the failure.

This movement, if left uncontrolled, could have destabilized the main body of the debris. The containment was achieved by building an arch-shaped bulkhead, founded in the stable substrate using 20 meters long, large diameter piles (diameter = 100 cm). The bulkhead was reinforced with a double row of 25 meters long tie rods, inclined at 20° (Fig. 11b). Two drainage branches were realised upstream of the containment work, collecting the water into the Campone stream. The concrete wall of the bulkhead was masked with boulders to mitigate its visual impact (Fig. 11c).

Fig. 11 - a) Aerial photo of the two first works carried out for the stabilization of the 2014 rockfall deposit along the Campone valley. Legend: 1 - the downstream structural work; 2 – the upstream structural work; 3 - the Campone stream. b) the downstream structural work was founded on large diameter piles (1) and strengthened by a double line of active nails (2 and 3); c) boulders were used to reduce the environmental impact of both structural works

Fig. 12 - The Campone stream (sky blu arrows) buried by the 2014 landslide deposit. The dotted white line is the boundary between shales and landslide deposit

The second containment work was carried out by utilizing the foundation of an old gabion constructed in the 1980s. The gabion was destroyed by the 2014 landslide but its foundation, consisting of a large beam anchored to structural wells 12 meters deep and 5 meters in diameter, remained intact. A retaining wall was built and anchored to the exhumed foundation and reinforced with spurs. Also in this case, an upper layer of boulders greatly diminishes the visual effect of the construction.

Monitoring the scarp and the debris accumulation underneath is currently in progress using an aerial photogrammetric technique with a drone. This method helps us to observe any movement in the debris from the 2014 failure, as well as changes in the rock wall conditions. This monitoring allows to assess the effectiveness of the interventions conducted in the Campone valley. To date, no movements of the debris deposit as a whole have been found, excluding small superficial flows. The deposit remains firmly against the wall (for further information, see Dubbini & Lucente, 2018). Two inclinometers installed in the foundation piles of the lower retaining structure also indicate stability.

Fig. 13 - The steel pipeline for bypassing the 2014 landslide deposit

The failure of 2014 completely buried the Campone gully, leading to an underground water flow at the contact between the debris and the basal clays (Fig 12).

Over time, due to the concentrated circulation of water, we began to witness a progressive sinking of the debris mass, an erosive phenomenon that could lead to the destabilization of the entire debris accumulation. This made the drainage of water a priority in order to bring the course of the Campone stream back to the surface. For this purpose, the old route of the Campone stream was restored with the construction of an inspectable, steel pipeline to bypass the debris accumulation (Fig. 13).

A further intervention was carried out at the northeastern corner of the San Leo cliff, on the edge of debris deposit of the 2014 event, to prevent a landslide that was moving at the base of the eastern wall, once more due to undermining at the foot of the wall (Fig. 14a). To halt the progression of the landslide, a structural intervention was implemented.

This involved constructing a reinforced pole-supported concrete bulkhead to contain the unstable mass. The retaining work has an irregular planimetric shape to incorporate a large, in place boulder. Totally, the work is approximately 40 m in length (14b). It features vertical poles measuring 100 cm in diameter and 20 m in length: these poles are arranged in a quincunx pattern across two rows to enhance resistance to counteract mud and earth flows.

The poles, drilled and cast in place, are inserted for two-thirds of their length into the substrate and are connected at the head by a 1 m thick slab. This slab supports active 5-strand harmonic steel tie rods inclined at 25°, placed at a distance between centres of 3 m (Fig. 14b).

The structural work is completed by a layer of large boulders, built on top of the reinforced concrete slab. Finally, sub-horizontal drains and drainage trenches were created to collect the water upstream to the retaining work. All the water collected is finally channelled into the Campone stream.

In light of these initial interventions, although significant progress has been made in stabilizing the 2014 landslide accumulation, it is crucial to keep up with stabilizing the slope strip next to the cliff and to address the Campone stream to avoid further erosion of its bottom. For this purpose, the initial consolidation efforts on the slopes at the bottom of the eastern cliff have been planned and initiated. Furthermore, as part of arranging the area at the foot of the cliff, it is essential to set up an integrated monitoring system network (including inclinometers, piezometers and target for topographic survey) to control the debris deposit and verify the efficiency of the completed stabilization works.

As a last stage, to complete the stabilization interventions in the Campone valley, it is also necessary to proceed with the restoration of the "Rio Maggio" stream. Several check dams built in the 1960s and 1970s have collapsed or have been damaged by floods, landslides and erosion. The benefits that can be obtained from an intervention

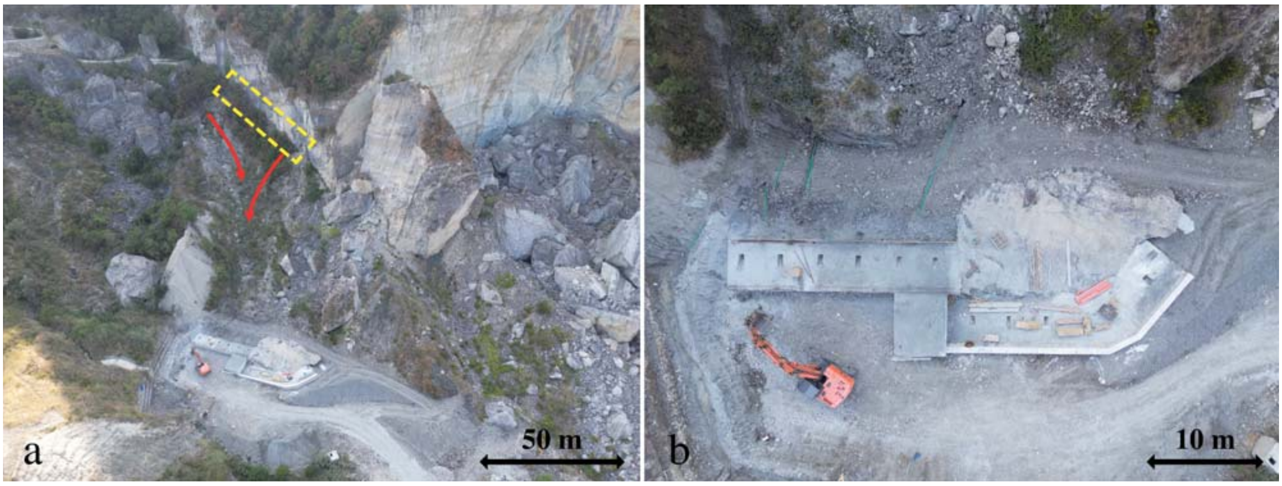

Fig. 14 - a) The structural work to contrast the movement of large earthflows (red arrows) causing undermining of the east face (yellow rectangle); b) the irregular shape of the retaining work to incorporate a large boulder

to regulate the bed of the “Rio Maggio” stream have positive effects on the Campone area (and the Seripa area too) and, in the long run, could also help to stabilize the clayey slopes at the base of the cliff.

Consolidation of the eastern rock face

The studies made after the 2014 event identified a second priority for intervention, focusing on the eastern face of the San Leo cliff, in the hairpin turn area of the access road to the fortress, which passes just a few meters from the edge of the wall (Fig. 15a and b). The knowledge acquired on the cliff setting (core drilling and geo-structural surveys on the wall and on the summit) and the analysis of the rock mass stability conditions have revealed a significant risk in the area. As a result, it has been deemed necessary to include in the civil protection plan a restricted access to the road, allowing only authorized shuttles during specific time slots and with operational monitoring equipment (see Fig. 10; Lucente, 2014).

The consolidation intervention carried out so far aimed to improve the safety conditions of the access route to the fortress. For the structural and geotechnical characterization of the rock mass for intervention design purposes, we referred to the studies and surveys conducted during the emergency phase. In addition, further boreholes were drilled along the road approaching the San Leo fortress: they provided for more detailed information of orientation and aperture of discontinuities both through the analysis of the cores and through video inspection.

The rope abseils survey revealed the presence of a large rock block parallel to the road. This block is separated at the rear by a major vertical crack belonging to the K1 system and at the base by extensive fractures belonging to the K4 family (see Fig. 7b). The most likely instability scenario involves plane sliding of a large block on a K4 base joint dipping outwards the cliff and the tensile opening of a nearly vertical fracture, running roughly parallel to the cliff face, belonging to the K1-K2 joint family. The potentially unstable rock portions could be laterally delimited by nearly vertical joints, with a wide opening angle in relation to the cliff face (60-70°), part of the K3 joint family.

The sizing of the consolidation intervention (density of bars required and their best arrangement) was established through a series of limit equilibrium analyses (Lembo-Fazio, 2017), which led to defining the intervention scheme represented in an example section of the wall (Fig. 15c). Without delving into the specifics of the stability analysis, which are beyond the scope of this article, the results indicate that the chosen reinforcement scheme is effective. It notably enhances the stability of the east wall along the access road to the fortress.

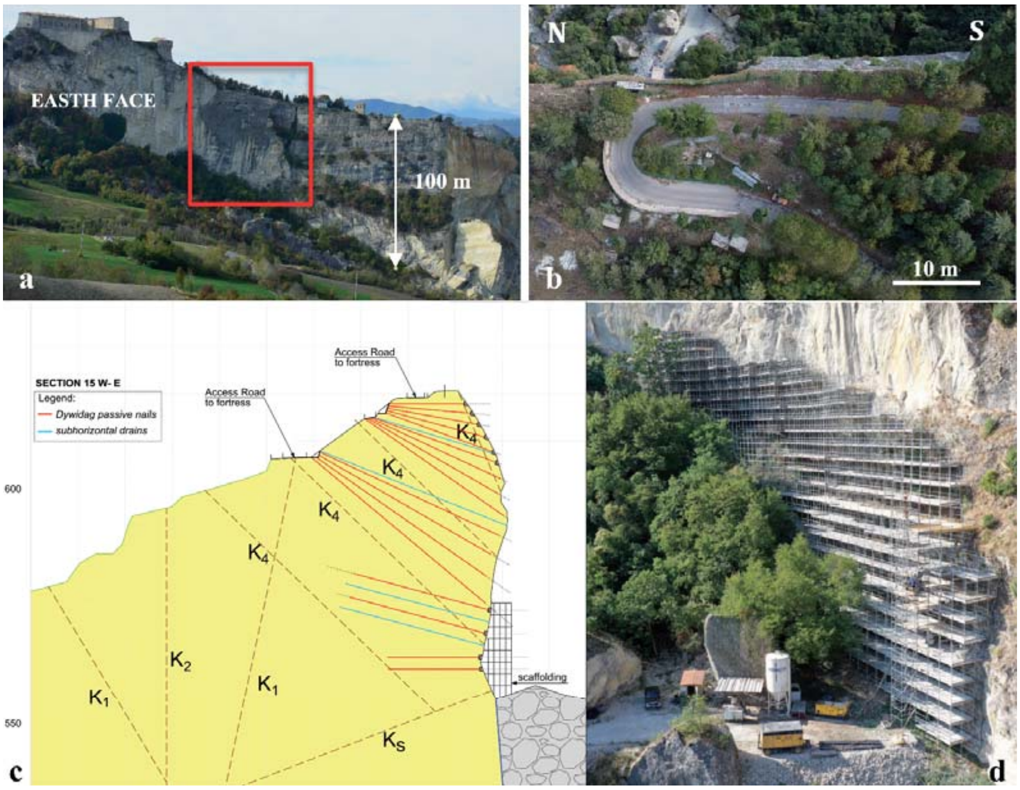

Fig. 15 - a) The portion of the east face that has been consolidated. b) bird’s-eye view of the intervention area. c) the design intervention scheme with a first group of nails made at the top of the cliff (perforation towards the outside of the rock mass), and a second group made at the base (perforation towards the inside of the rock mass). Red line=Dywidag passive nails; blue line=sub horizontal drains; K4 and K1=fractures; Ks bedding. d) the scaffolding for installing the passive bars at the base of the face (east face of the cliff)

Fig. 16 - The south face of the San Leo cliff divided in three sectors: A, under the San Leo village; B and C, above the access road to the village

The chosen intervention involves installing a system of passive steel bars deep into the rock mass (up to 50 ÷ 60 meters) in holes with various orientations. The bars, with diameters of 26.5 mm and 32 mm, are anchored to the rock along their entire length by injections of cement grout.

The choice of passive reinforcement is mainly motivated by the need to avoid the risks associated with the decrease of roughness along discontinuities or with the damaging the rock bridges found in between the discontinuities. The application of high pretension loads, as typical of active tie rods, could destroy joint roughness (decreasing of resistance) and promote stress increasing to rock bridges which could cause brittle failures. Furthermore, the complete cementing of the bars, done through low-pressure injections, can promote the sealing of discontinuities intercepted during the perforations.

The consolidation was carried out both on the top of the cliff, with perforations directed towards the external face, and from scaffolding built at the foot of the wall, with perforations directed from the wall towards the interior of the rock mass (Fig. 15c). For the bars located at the top, the spacing between their centres in the vertical direction of the project sections is 5 m. For the bars built at the base of the wall using scaffolding, a distance between centres of 2.5 m was used.

Overall, 13,200 m of steel bars were installed. Upon completion of the reinforcement intervention, a total of 2,350 m of deep drainages were created. In some of the holes, video inspection was carried out to thoroughly and systematically monitor the fracture condition for ongoing updates on the discontinuity network.

Consolidation of the south rock face

As for the southern side, significant progress has been made in reducing the risk and safeguarding the town, its sole access road, and the fortress on the southeast corner of the cliff, thanks to the interventions implemented over nearly 40 years (Fig. 16). However, the progressive alteration of the rock subjected to atmospheric and other external agents, occasional small collapses, and the lack of maintenance on completed works need attention. This is particularly important in terms of risk exposure and the vulnerability of the assets involved. Therefore, in recent years, especially following the dramatic event of 2014, there has been a need to implement additional measures to reduce risk. For this purpose, leveraging prior knowledge, a multidisciplinary study was carried out following the same approach used at the 2014 event. This involved photogrammetric and topographic surveys, geo-structural assessments, geomechanical analysis of the rock mass, stability evaluations, deep core drilling from the cliff's top to the clayey substrate, and laboratory tests. A detailed geological survey was conducted using mountaineering techniques to determine the structural layout and geomechanical properties of the walls. The geological survey allowed to identify the main discontinuities, the unstable volumes (Fig. 17), and to check the works already made on the wall. The results of the geo-structural survey emphasized the necessity to conduct consolidation interventions on the southern slope of the cliff. This need is further underscored by the ongoing high-risk conditions, despite previous intervention efforts.

A first proposed intervention has already been financed and started and concerns sector A of the southern face of the cliff below the town (Fig. 18). This is the continuation of interventions carried out in the past (Caturani *et alii*, 1991; Lucente, 2019). Also in this case, passive anchors were preferred for the same reasons expressed above. The intervention scheme (position, length, thickness, and inclination of the bars) is determined through numerical analysis at limit equilibrium (Lembo-Fazio & Graziani, 2021). The intervention sector was divided into

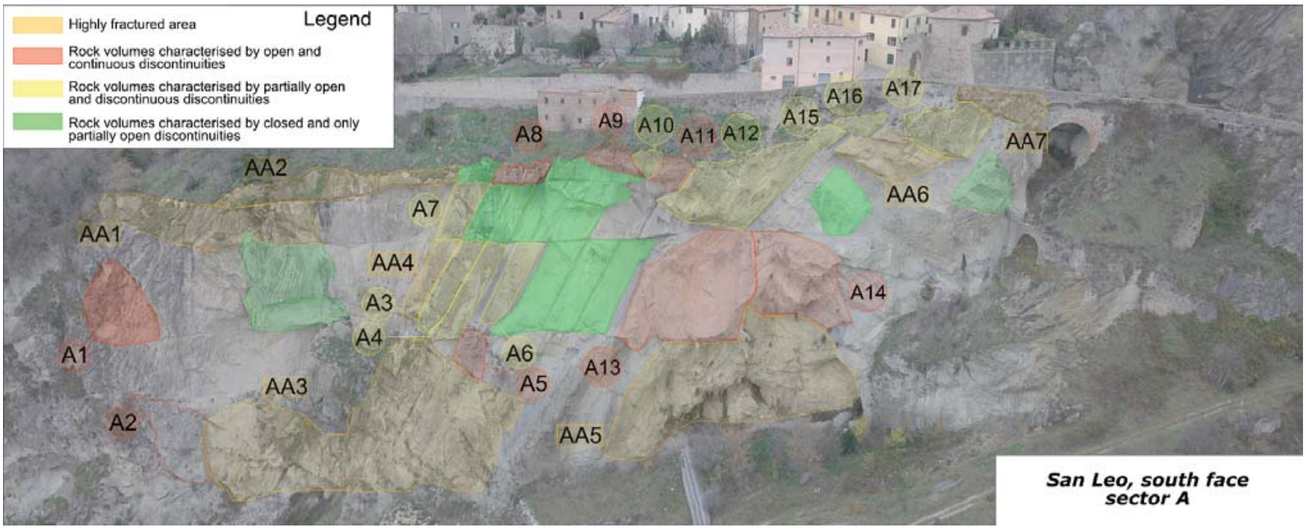

Fig. 17 - Representation of the unstable rock volumes in the sector A - blocks and/or rock portions with three different degrees of danger were identified: P1=high to very high danger; P2=medium danger; P3=low danger

three areas (Fig. 18a in prospect, Fig. 18b, in section). At the summit strip (intervention 1), 40 m deep bars, with a diameter of Ø 32 mm, inclined 25° downwards and with a mesh pattern with a pitch of 2.5 m, were laid in a clear overhang. In the intermediate band (intervention 2), the plan included using 12-meter-deep bars, with a diameter of 26.5 mm, inclined 15 degrees upwards, and arranged in a mesh pattern with a pitch of 2.5 meters. To carry out interventions 1 and 2, a drilling slide lowered along the wall was used (Fig. 19).

At the summit strip (intervention 1), 40 m deep bars, with a diameter of Ø 32 mm, inclined 25° downwards and with a mesh pattern with a pitch of 2.5 m, were laid in a clear overhang. In the intermediate band (intervention 2), the plan included using 12-meter-deep bars, with a diameter of 26.5 mm, inclined 15 degrees upwards, and arranged in a mesh pattern with a pitch of 2.5 meters. To carry out interventions 1 and 2, a drilling slide lowered along the wall was used (Fig. 19).

Finally, in the lower band (intervention 3), bars 12 meters deep with a diameter of 26.5 mm will be used, inclined 15 degrees upwards. They will have a mesh pattern with a pitch of 2.5 meters. Additionally, bars 40 meters and 30 meters deep, with a diameter of 32 mm, inclined 15 degrees upwards, and with a mesh pattern having a pitch of 5.0 meters, will be utilized. In this area, the intervention will be conducted with the use of scaffolding.

A second intervention, awaiting financing, concerns sectors B and C of the south wall (Fig. 16).

In the past, the amphitheatre shaped rock wall (sector B) has undergone reinforcement and consolidation interventions. These actions included localized anchoring, rope bindings, and underwalls to stabilize rock volumes prone to fall. However, recent investigations on the wall have still highlighted the presence of very dangerous conditions caused by rock volumes in precarious equilibrium. To further decrease the risk in sector B, it was necessary to evaluate the requirement for individually stabilizing the most hazardous large rock masses by using localized nailing with steel bars having a diameter of 32 mm, anchored in sound and stable rock for a minimum of 5 meters. The sizing (number and depth of bars) of the intervention at limit equilibrium was determined based on the characteristics of the discontinuities and the failure mechanism (wedge sliding and planar sliding). Furthermore, at the base of the "amphitheatre" a rockfall barrier will be constructed. It will have a height of 6 m, a length of 30 m, and an absorption energy of 3,000 kJ. This barrier will be placed to safeguard the road below, ensuring safety during the temporary phase while the rock wall works are ongoing. It will also serve a long-term purpose by intercepting smaller rock volumes that are not impacted by the "active" consolidation in the wall. The size and position of the rockfall barrier were determined statistically by simulating rock falls.

Even the rock face below the fortress (sector C, Fig. 16) has undergone reinforcement and consolidation in the past through nailing (LUCENTE, 2019 and references therein). This process aimed to secure the loose superficial rock layer (superficial nailing) by anchoring it to the solid rock beneath (deep nailing) (D'AMBRA *et alii*, 2004).

From the analysis of the interventions, carried out in several phases across the entire rock face of sector C, it is assumed that the deep consolidation of the rock mass has been achieved.

However, the high level of cortical fracturing in the mass requires better surface stabilization. Today, the debris resulting from dewatering of highly fractured portion of the wall is contained by a basic double-twisted metal mesh. While it has managed to retain some small debris, as shown by the pockets of material gathered in

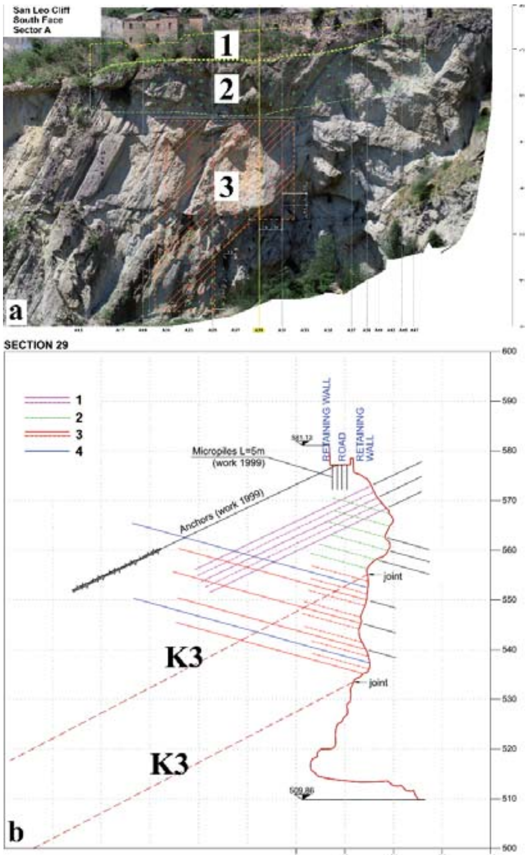

Fig. 18 - *a) Design scheme (prospect) of the consolidation intervention of the sector A, along the south face of San Leo cliff. From top to bottom, the intervention area was divided into three bands. Legend: 1 –the upper band; 2 – the middle band; 3 – the lower band; b) Design scheme of the consolidation intervention of the sector A, in section. In the uppermost portion of the face, the bars are 40 m long and inclined downwards by 25° (violet traces); in the middle portion the bars are 12 m long and inclined upwards by 15° (green traces); finally, in the lowermost portion the bars are 12 and 40 m long and inclined upwards by 15° (red traces). Note the marked overhang of the face*

Fig. 19 - *Rock drilling operations with mountaineering technique before the subsequent installation of the bars*

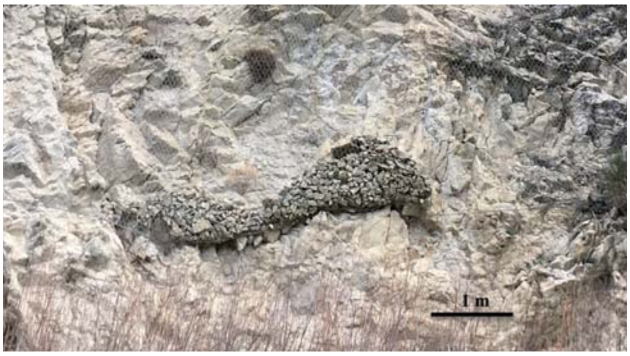

Fig. 20 - *Small-block debris retained by the hexagonal metal mesh net*

different areas (Fig. 20), it is not enough to ensure safe conditions. In addition, it should be noted that the net is damaged in several places and occasionally small blocks of rock fall to the ground. As a result, it is specifically intended to strengthen the wall by utilizing double-twisted wire mesh (8×10 mm hexagonal mesh) and rectangular steel wire mesh panels (6×3 m, 300×300 rhomboidal or square mesh, frame Ø = 8 mm), which will be fixed to the wall and connected to the mass using Gewi bars (Ø = 25 mm, L = 6 m).

The panels are equipped with perimeter steel ropes Ø = 14 with fixing to the top and foot of the rock face using steel ropes Ø = 16. The connection between adjacent network panels and the connection between the network and the anchors are created by steel cables with a metal core with a diameter of Ø = 10. The intervention aims to stabilize only what is defined as 'cortical instability'. These are small rockfall events that impact only the outer layer of the exposed rock mass.

FINAL REMARKS

San Leo is the main fortified city of Montefeltro. Its fortress has been an impregnable location for centuries, thanks to its unique geographical position atop a cliff surrounded by high, steep rocky walls. However, this location has been costly for the city of San Leo and its fortress. Over the centuries, the area has been heavily affected by large landslides predisposed by the unique geological and geomorphological structure of the cliff.

Coexistence with these large landslide phenomena has historically led to multiple modifications of the access routes to the village and the fortress.

Only in more recent times, after some important failures in the middle of the last century that threatened the entrance gate and the town and involved portions of the fortress, were the first interventions started to mitigate the risk. Since the late 1960s, several interventions have been implemented, leading to significant improvements in safety and risk reduction. However, even after the recent collapses, which involved large volumes of rock, the risk level remains high. This is particularly true in certain areas of the cliff, where the intensity and danger of landslides are significant due to high exposure and vulnerability.

The complexity of the instability mechanism and the stress state in the rock mass and fractures need special consideration when looking for effective solutions to address instability. In addition to the standard rock mass consolidation works to secure rocky walls, it is crucial to also carry out interventions that help minimize the hazard caused by erosion and destabilization of the clays at the base of the calcarenitic rock walls. This is what was done with the first interventions carried out in the Campone valley and in the Seripa valley with the aim of counteracting the undermining of the rock walls.

The collapses in the Campone stream valley, despite the works done in the 1980s, likely happened because the intervention was too small, lacked maintenance, and without monitoring data underestimated how quickly the instability was evolving. Only later, towards the end of the 1980s, did the initial monitoring begin and investigations intensify to gather the understanding of landslides. This knowledge, albeit limited to specific areas, was crucial for planning and executing targeted interventions. After the failure of 2014, a comprehensive and interdisciplinary study began. This study allowed for the creation of risk scenarios, the establishment of an initial geological and hydrogeological model of the cliff, the identification of the main discontinuity sets within the rock mass, and the exploration of the reasons and mechanisms behind the slope instability processes. Furthermore, a fracture monitoring system in operation since April 2014 continues to provide interesting data on the behaviour of the rock mass. After managing the emergency challenges, the acquired knowledge enabled the initiation of risk reduction actions on the north and east sides of the San Leo cliff following the failure of 2014. Subsequently, attention was also given to the south face, which is undoubtedly the most critical in terms of exposure and vulnerability. As proof of the value of knowledge, an accurate assessment of the hazard of the south face has led us to consider it essential to conduct consolidation interventions on this side. This includes the setting up of a monitoring system for assessing the effectiveness of the interventions carried out.

Finally, it remains important to emphasize the necessity of planning maintenance for both completed interventions and those yet to be carried out. This will help ensure a longer life of the works carried out. The works' maintenance is very important to deal with the morphological changes happening at the base of the rocky cliff due to landslides. In recent decades, these changes have accelerated significantly due to the changing climate conditions.

Certainly, the plan to effectively address slope instability and ensure acceptable safety conditions (aiming for the lowest possible risk) comes with high costs. These costs are in addition to those already spent over 70 years of interventions. However, they are justified not only in ensuring public safety but also in the invaluable historical and cultural significance of San Leo. The municipality was in fact recognized as a "jewel of Italy" by the Ministry of Tourism in 2013.

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