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Instability mechanisms affecting cultural heritage sites in the Maltese Archipelago

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Abstract. The superimposition of geological formations with marked contrast in geotechnical properties presents one of the most critical environments for slope instability due to the different response of the materials to the applied disturbances. Moreover, the above-mentioned geological setting is often associated with high risk conditions, since many isolated rock slabs located at a higher altitude than the surrounding countryside have been sites of historical towns or buildings.

The purpose of the present paper is to investigate the mechanisms determining instability in rock slabs overlying a soft substratum, with reference to two cultural heritage sites in Malta. Accurate investigations have been carried out to evaluate the geological, geotechnical and geomechanical properties together with the main geomorphological features of the soft clayey substratum and the overlying limestone rock mass.

The main instability processes have thus been identified and investigated through kinematic analyses and numerical modeling, combined with a 1992–2001 Persistent Scatterers monitoring of ground displacements. The study constitutes the basis for the subsequent restoration works.

1 Introduction

The overlapping of hard rock masses, potentially subjected to elastic deformations and brittle collapse, on a plastic substratum is a common geological feature, especially in cultural heritage sites (Cancelli and Pellegrini, 1987; Canuti et al., 1990, 2004; Bertocci et al., 1991; Casagli et al., 1993; Katz and Crouvi, 2007).

This superimposition frequently leads to mechanical instability due to the diverse response of the materials to the applied perturbations, such as man-made excavations, weathering or erosion. The latter acts selectively, with major impacts on the more erodible substratum, thereby forming buttes or plateaus above the surrounding countryside, bordered by unstable steep cliffs. Such a type of configuration evidently generates conditions of high hazard associated with a relevant vulnerability and related risk for built heritage of significant cultural value; threats to people's safety can derive as well (Cestelli et al., 1984; Cotecchia, 1997; Canuti et al., 1999; Luzi et al., 2004; Egglezos et al., 2008).

We should carefully distinguish in detail the overall mechanism which governs the behavior of a rock slab over a soft substratum from the failures that take place at its boundaries. Only the latter can be classified according to the traditional landslide classification schemes. The former can be defined as a complex mass movement, according to Varnes (1978) and Hutchinson (1988), since it involves a combination of several different basic failure mechanisms

Therefore, the problem requires a multi-disciplinary approach involving the application of principles from different fields, such as rock and soil mechanics, geology, geomorphology, engineering geology, and conservation sciences.

According to Casagli (1992), the instability mechanisms affecting this geological environment can be classified into three different but strictly interconnected types:

- overall mechanism of instability;
- soil slope instability;
- rock slope instability.

As regards the overall mechanism, the contrast in stiffness of the outcropping materials causes the opening of joints and new tensile failures (Casagli, 1992); both isolate large blocks that can be involved in marginal mass movements (Fig. 1). The fracturing and opening of joints produce stress redistribution at the boundary between the rock plate and the substratum. Thus, vertical relative displacements of rock blocks may also take place due to local elastic-viscous settlements and yielding.

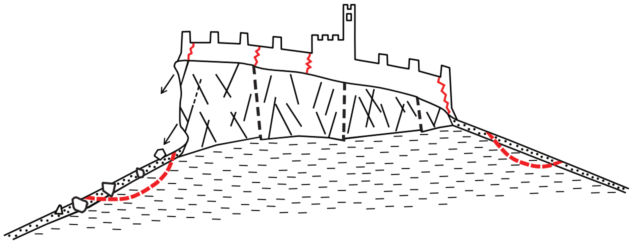

Fig. 1. Simplified sketch of the instability mechanisms affecting a rock slab overlying a soft substratum.

Associated with these mechanisms, a slow downward and outward extrusion of the clayey material underlying the rock slab may occur, providing potential material involved in landslides and earth flows. This class of movement, known as squeezing-out and bulging, is described in detail by Zaruba and Mencl (1982).

If the rock plate is wide and thick and the mechanical properties of the involved materials are very different, various large scale and slow moving complex phenomena may occur, known in the literature as lateral spread (Varnes, 1978), cambering and valley bulging (Hollingworth et al., 1944; Horswill and Horton, 1976; Parks, 1991), and block type slope movements (Pasek, 1974).

The overall mechanism of instability also contributes to the enhancement of the phenomena, which take place both on the ductile substratum and on the rock plate.

The most common failure mechanisms affecting the underlying soft substratum are rotational or compound slides (Hutchinson, 1988) and earth flows (Varnes, 1978; Hungr et al., 2001). These can also be influenced by the accumulation of material which has fallen from the rock cliff, causing surcharge (Zaruba and Mencl, 1982; Casagli, 1992). On the other hand, landslides at the base of the rock slab undermine underlying support and trigger further block movements.

The subvertical and jointed rock walls can be affected by a great variety of mechanisms, such as rock falls, rock slides, toppling (either forward or back tilting), and differential settlements. Rock slope failure at the border of the slab increases the stress relief, and causes the spread of the instability phenomena.

The great variety of interconnected instability mechanisms affecting a rock plate – soft substratum system is therefore able to produce great damage to structures or buildings built either on the rock plate or at the base of the rock walls (Fig. 1).

The geological setting of the Maltese Archipelago often shows the overlapping of relatively stiff and brittle limestone plates on thick clayey units. This leads to typical geomorphological processes, such as slides or flow phenomena in the underlying ductile units and brittle ruptures involving the overlying rock masses. The latter are often affected by huge sub-vertical joints that isolate large blocks. In this paper we present the analysis of the stability conditions of two important cultural heritage sites in the Maltese Archipelago: Mdina in Malta and Citadel in Gozo (Fig. 2). Due to their natural and historical importance, both sites are included amongst the main touristic destinations of the Archipelago.

2 Description of investigated sites

2.1 Maltese geology

Malta and Gozo Islands belong to the Maltese Archipelago, central Mediterranean Sea (Fig. 2a), standing on a shallow submarine elevation, the Malta plateau, part of the Pelagian Platform (Bowen Jones et al., 1961; Pedley et al., 1978; Schembri, 1993, 1997; Magri, 2006) (Fig. 2b).

The landscape is geomorphologically characterized by gently rolling hills with terraced fields (the highest point of the archipelago lies at about 250 m a.s.l.), while steep sea cliffs delimit the south-western coastline (House et al., 1961; Vossmerbäumer, 1972; Alexander, 1988).

The geological setting is constituted by marine sedimentary rocks, mainly limestones Oligo-Miocenic in age, subsequently lifted above sea level during the Pliocene period by a subvertical fault system related to the opening of the Pantelleria Rift (Reuter, 1984; Finetti, 1985; Alexander, 1988) (Fig. 2).

Among the five units lying almost horizontally across the Maltese Islands (Hyde, 1955; Pedley, 1974; Pedley et al., 1976, 1978; Bosence et al., 1981; Debono and Xerri, 1993; Pedley, 1993; Pedley et al., 2002) (Fig. 2c), the following ones are of particular relevance for the sites of Mdina and Gozo:

- Blue Clay Formation (BC): a very soft pelagic blue or greenish grey marl and limey clay, ranging from middle to upper Miocene in age, forming gentle hillslopes mostly covered by soil or scattered rubble. Its thickness varies approximately from about 20 m to 75 m.

- Greensand Formation (GS): massive, friable brown to dark green glauconite and gypsum grain-rich bioclastic limestone, Tortonian in age. This formation is rarely more than 1 m thick, and can occasionally expand to over 10 m at the base of hilltops in central Gozo.

- Upper Coralline Limestone Formation (UCL): over 160 m thick, it consists of pale grey to orange fossiliferous coarse grained limestone, ranging from upper Tortonian to early Messinian in age, and it is made up of four members, the basal one of which is referred to as Ghajn Melel Member (Mgm).

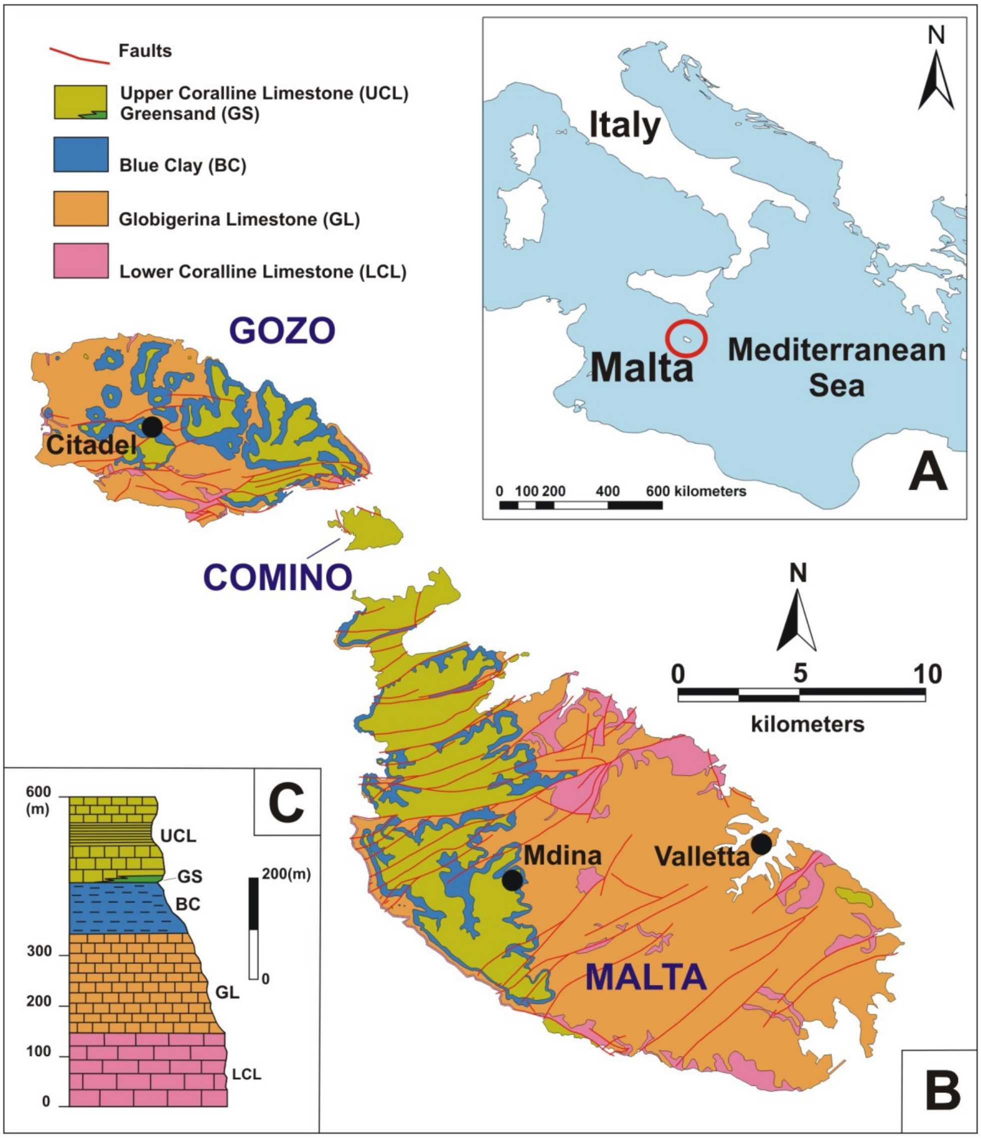

Fig. 2. Geographic setting **(A)**, simplified geological map **(B)** and stratigraphic column **(C)** of the Maltese Archipelago (modified after Pedley et al., 2002).

UCL hillcaps and plateaus overtopping BC gentle slopes are the dominant feature in the landscape of north-western Malta and north-eastern Gozo (Fig. 3a, b). Therefore, the geological and geomorphological features of the latter areas are deeply influenced by the geological characteristics and mutual interaction of the above-mentioned formations (Magri et al., 2008; Devoto et al., 2011), while GS, due to its limited thickness, can only affect the form of the land surface locally.

2.2 Geological setting of the investigated sites

Mdina and Citadel (Fig. 3c, d) are built on two hills belonging to the many that characterize the Maltese and Gozitan landscapes. These reliefs owe their existence to the deeper erosion of the land that surrounds them (Scerri, 2003). All of them are characterized by sub-horizontal or gently inclined UCL cap protecting the underlying soft BC slopes. Although the geological materials and the stratigraphic sequences are similar, the investigated sites show quite diverse instability problems, due mainly to the different thickness of the outcropping formations and to specific geological features.

UCL, being at the top of the Maltese Islands stratigraphic sequence, is particularly subjected to the action of eroding factors: percolating rainwater dissolves the limestone, forming fissures and caves, stopping when it reaches the impermeable barrier of the underlying BC. When the contact of these two units meets the land surface, spring lines may develop, contributing to undermining the limestone hillcaps'

Fig. 3. Panoramic views of UCL slabs overlying BC exposed in Gozo **(A)** and Malta **(B)**, and of the investigated sites of Mdina **(C)** and Citadel **(D)**.

stability. Furthermore rainfall washes away the easily erodible BC causing the overtopping limestone caps to break away and collapse into blocks of various sizes (Fig. 3d) (Pedley et al., 2002).

2.3 Mdina

Mdina, the former capital of Malta, is a fortified town located in the central – western sector of the Island on a rise constituted by the UCL (Fig. 3c). Thanks to its strategic position, over the past centuries the city has been influenced by many cultures. In 1693 it was extensively damaged by the Val di Noto (Sicily) earthquake (Galea, 2007), and most of the buildings and bastions were constructed afterwards (De Lucca, 1993). The city is built on a thin UCL plate (maximum thickness: 6 m) with a rhomboidal shape and a total surface area of about 55 000 m^2.

From a geomorphological point of view, the main landforms associated with the geological system described above are always hidden by anthropic structures, and can only be observed on the nearby hills, where the landscape is much less modified by human activities. Due to the thinness of the rock plate, the structures are often built over the contact between the UCL/GS and the underlying BC, thus increasing the instability problems due to differential settlements of the structures.

For this reason, most of the damage to buildings and bastion walls is located in the perimetral sectors of the city (Baratin et al., 2001; Bonnici et al., 2008) (Fig. 4), and is concentrated in three specific areas, namely Vilhena Palace, Cathedral and Curtain Magazines.

2.4 Citadel

Citadel is a small fortified town (Fig. 3d) located in the central part of Gozo, on a hilltop located above the town of Victoria (also known as Rabat). Given its central and panoramic location within the island of Gozo, this vantage point has hosted urban settlements since the Bronze Age.

The hill consists of more or less circular UCL rock plate, which is 20 m to 25 m thick and about 150 m wide, overlying first a layer of GS and then gentle BC slopes.

The rock plate slopes are sub-vertical, sometimes overhanging, while the underlying slopes are mostly

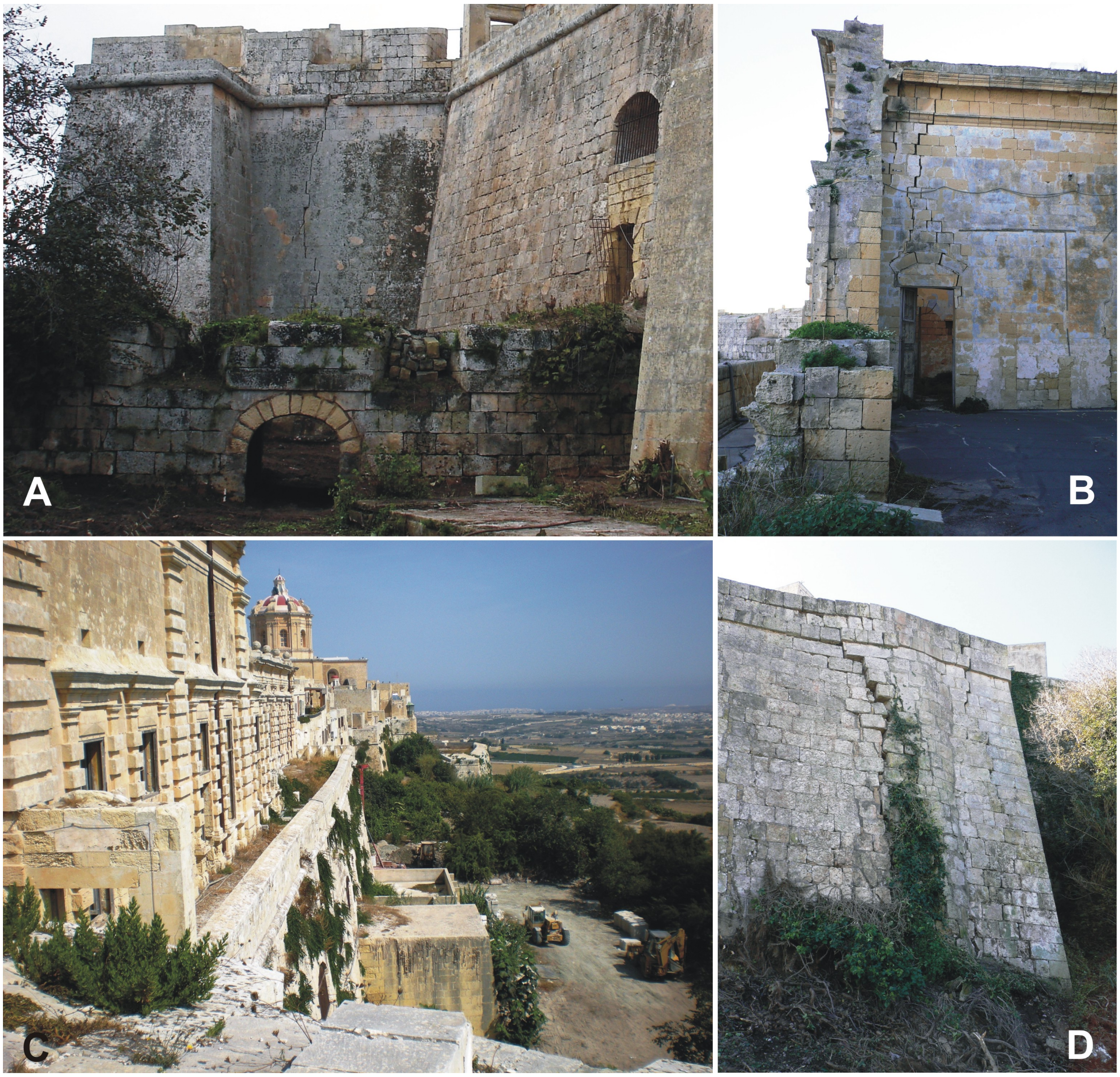

Fig. 4. Structural damages affecting Mdina bastions, walls and buidings. **(A)**: St. Paul's Bastion; **(B)** and **(C)** : Vilhena Palace; **(D)**: Despuig Bastion.

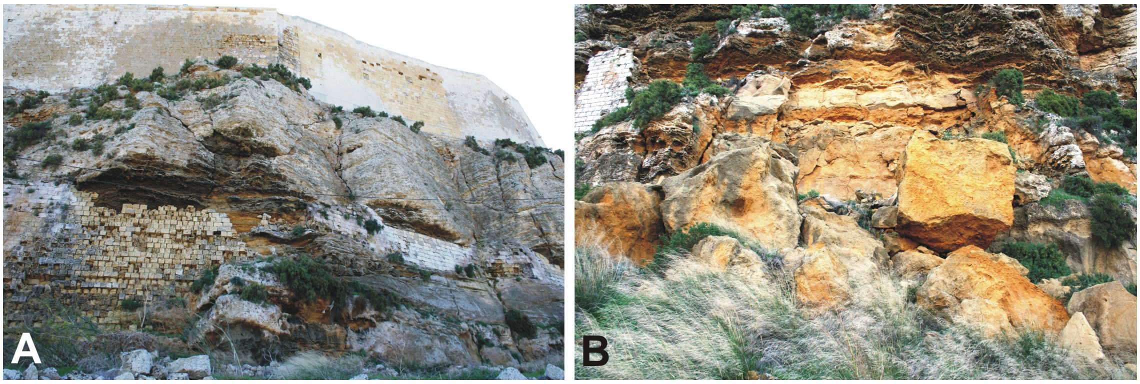

Fig. 5. Instability mechanisms affecting the UCL rock plate underlying Citadel (**A**: rock mass and underpinning masonry; **B**: rock fall debris).

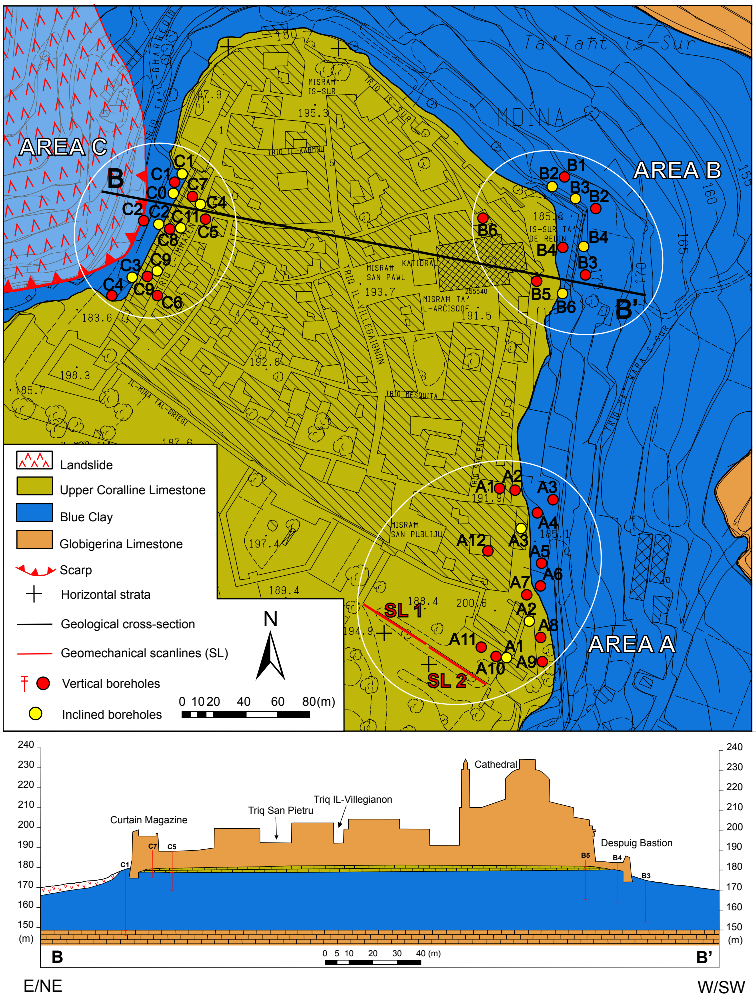

Fig. 6. Geological map and cross-section of Mdina. Area A: Vilhena Palace; Area B: Cathedral and Despuig Bastion; Area C: Curtain Magazines.

characterized by very gentle to gentle steepness (from 10 % to 20 %).

The rock mass shows a high degree of fracturing, and is constituted by layers having different resistance to erosion, leading to the formation of ledges and niches (Fig. 5a); these factors cause the detachment and falling of rock blocks of various sizes. On the northern sector of the cliff, a large rockfall event took place in December 2001, and the resulting debris is still evident (Fig. 5b).

Evidence of previous rockfalls is also visible slightly east to the event which occurred in 2001. In order to inhibit these rockfalls several underpinning masonry structures were built in the past, with the purpose of protecting the niches which are the most eroded portions of the outcropping cap rock, and to improve its global stability. These structures, widely present on the northern and eastern side of the cliff face, were built in different periods, and many of them are now in a poor state of repair (Fig. 5a).

From a structural point of view, although extensive evidence around the fortification walls shows rebuilding of structures due to cliff face retreat, the only signs of deformation are related to differential displacements of the few structures built on the contact between different materials.

3 Data collection

3.1 Geological survey

Accurate geological, geomorphological and geomechanical surveys of the selected sites were carried out with the aim of investigating the causes of the main instability processes and determining the material properties to be subsequently used during the analysis phase.

In particular, high resolution geological maps and related cross-sections were drawn utilizing the detailed geological survey, carried out by means of a differential GPS survey, in

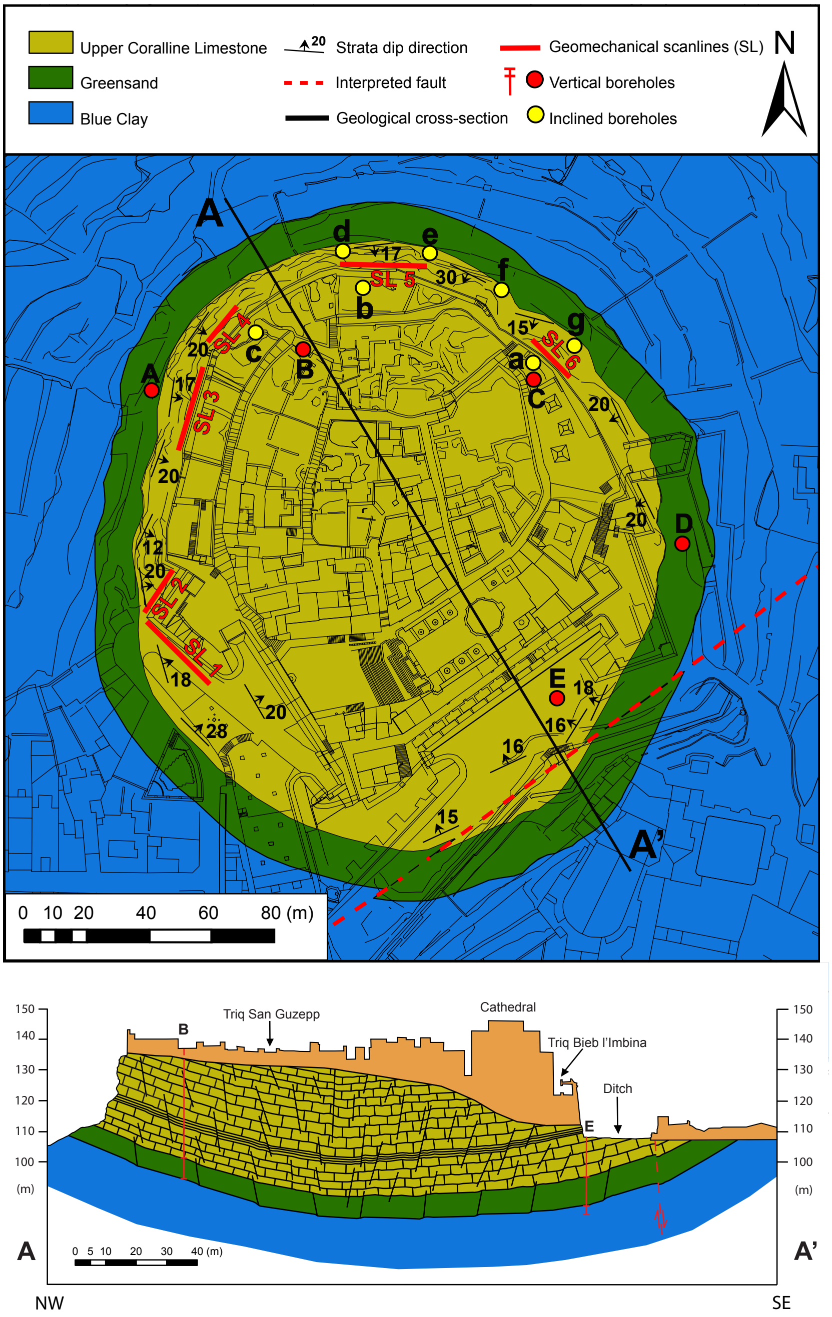

Fig. 7. Geological map and cross-section of Citadel.

order to reconstruct, with centimeter accuracy, the 3-D geological model and its geometric correlation with the man-made structures.

The traditional geological surveys have been integrated with a number of ground (deep vertical boreholes; Figs. 6 and 7) and structural investigations (horizontal and inclined boreholes), carried out by Ballut Blocks Services Ltd. (Mdina) and Solidbase Ltd. (Citadel).

Furthermore, a geotechnical characterization has also been carried out by means of laboratory tests on undisturbed rock and soil samples retrieved from the deep and inclined boreholes (Tapete et al., 2012).

As regards Mdina the stratigraphic contact between the UCL and the underlying GS and BC is not regular, and some groundwater emerges on the clayey slopes in the form of minor springs along the scarps. The location of these minor

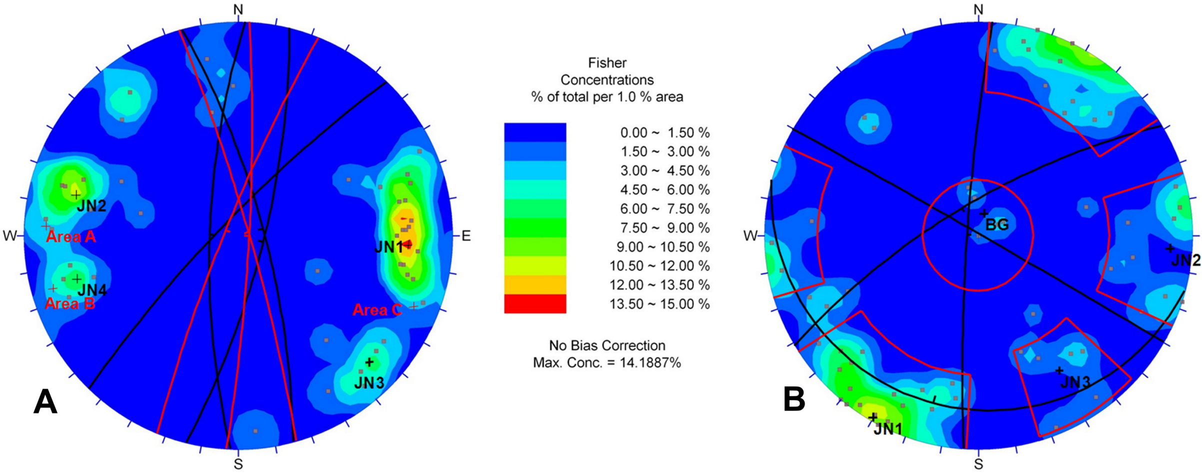

Fig. 8. Discontinuity poles, contour lines and modal planes of the main discontinuity sets collected at Mdina **(A)** and Citadel **(B)**. The mean buried rock-slope orientation of the Mdina areas investigated is also reported (red major planes).

springs is usually marked by the growth of many hydrophilic plants (such as reeds). Groundwater seeping out at the base of the plateau scarps in the form of gravity springs destabilizes the clay which then undermines the plateau. This process affects the scarp reducing shear strength and makes it prone to shear failure under the action of gravity.

Figure 6 reports the high resolution geological map and a representative cross-section for the Mdina site. Vilhena Palace (Area A), the Cathedral (Area B) and the Curtain Magazines (Area C), which display the most evident instability problems (Fig. 4), are shown with white circles in Fig. 6. The limestone bedding planes are parallel and almost horizontal. Here the GS formation is characterized by a minimal thickness (few centimeters), which makes it difficult to show on the map, and irrelevant with respect to the global slope stability. The geological cross-section also highlights the thinness of the UCL rock plate, being almost completely covered with man-made structures. This causes serious instability problems due to differential settlements of those structures built over the rock-clay contact. Figure 6 also reports the upper boundary of an area involved in a slope instability process, as observed from field surveys and from aerial images. This landslide is supposed to play a significant role in the structural instability, undermining the limestone plate right in the Curtain Magazine (Area C) foundation area.

As regards Citadel (Fig. 7), the rock outcrops of the cliff face are almost entirely constituted by UCL, here represented by the Ghajn Melel Member (Mgm), with the exception of a GS layer at the base of the hill cap. From the analysis of the retrieved borehole cores, this GS layer is about 10 m thick (Fig. 7); this value is comparable to the thickness of the same Formation outcropping at Gelmus Hill, less than 1 km WNW from Citadel.

The Ghajn Melel Member (Mgm), mainly consisting of a yellow to pale brown coarse grained organic calcarenite, shows persistent subvertical fissures and joints, which have triggered many rockfalls occurring along the cliff face perimeter. For its different internal sedimentary fabric and reaction to erosion, it has been subdivided into three distinct informal sub-members, which from top to bottom are:

- Upper Bank: having a massive structure, is directly located at the base of the bastion walls. It is characterized by a relatively strong resistance to erosion and to weathering processes.
- Thinly Layered Bank: it underlies the Upper Bank, differing from the latter for a thinly layered structure and for much less resistance to erosion. In fact it gives form to erosional niches, often covered by underpinning masonry structures.
- Lower Bank: it consists of the lower portion of the Mgm Member, overlying the cliff face base level of GS. Similar to the Upper Bank it shows a massive structure and a relatively strong resistance to erosion. It is sometimes covered by vegetation and rubble which limits its exposure.

The strata orientations collected all around the cliff show that the bedding planes always dip into the slope from the cliff perimeter towards the centre of the rock plate, with inclination angles ranging from 12° to 30° (Fig. 7). According to Pedley (1974) this structural setting is due to a solution collapse structure, late Miocene in age, like many others scattered all over the Maltese islands. Where the thick Miocene infill is softer than the surrounding materials, an erosional hollow is caused by selective erosion; instead when the infill is harder than the surrounding materials, because of a higher degree of litification, a circular erosional plateau (mesa) occurs (Pedley et al., 2002).

Table 1. Geomechanical properties of the rock mass discontinuities. Set_id: joint set identification code; α: dip direction; β: dip; X: true spacing; L: persistence; e: aperture; JRC: Joint Roughness Coefficient; JCS: Joint Compressive Strength; r: Schmidt hammer rebound number on wet and weathered fracture surfaces; R: Schmidt hammer rebound number on dry unweathered surfaces; ϕ_b: basic friction angle.

	Set_id	α (°)	β (°)	X (m)	L (m)	e (mm)	JRC	JCS	r/R	ϕ_b(°)
UCL Mdina	JN1	272	75	3.5	1.3	9.8	11.1	18.3	0.4	32.3
	JN2	104	76	7.0	1.6	15.3	12.8	17.4	0.5	32.3
	JN3	314	81	5.4	1.6	15.6	14.6	21.7	0.7	32.3
	JN4	075	76	7.8	1.5	21.4	13	20.1	0.5	32.3
UCL Citadel	JN1	030	89	1.4	2.5	13.3	12.1	15.6	0.4	35.9
	JN2	274	84	1.3	2.9	12.9	11.7	17.5	0.8	35.9
	JN3	329	73	5.1	2.6	17	13.7	16.9	0.6	35.9
	BG	0–360	12–17	1.4	Inf.	11	12	15.7	0.7	35.9

3.2 Geomechanical survey

The rock mass characterization and the quantitative description of discontinuities were obtained by means of traditional geomechanical surveys (scanline method), according to the methods suggested by the International Society for Rock Mechanics (ISRM, 1978, 1985).

Due to the limited rock mass outcropping at Mdina, only 2 scanline surveys (25 m and 30 m in length) were performed on the rockwall next to the ditch within the Vilhena Palace area (Area A) (Fig. 6). In order to extend the rock mass mechanical properties to the other investigated areas, some random discontinuity orientation measurements were taken, confirming the spatial distribution of the identified discontinuity sets.

As regards Citadel, a total of 6 scanline surveys (varying from 15 m to 33 m in length) were performed according to the methods suggested by ISRM (1978, 1985). These scanlines were performed all around the cliff face, to cover both the massive Upper and Lower Bank and the Thinly Layered Bank of the Ghajn Melel Member within the UCL Formation (Fig. 7).

For each scanline a sheet was filled by measuring the orientation, persistence, aperture, roughness, rock wall strength, filling, seepage of the discontinuities crossing the survey line.

In order to determine the UCL intact rock tensile and compressive strength for both investigated sites, a number of point load tests were performed, following the methods suggested by ISRM (1985). The resulting σ_c values for UCL intact rock are: 22.3 MPa (Mdina) and 6.7 MPa (Citadel).

With the aim of identifying the major discontinuity sets, orientation data were plotted on a stereographic projection (lower hemisphere).

Figure 8a reports the stereographic projection of the collected data: discontinuity poles concentration, main set modal planes and mean buried rock-slope orientation in the investigated areas are shown. Excluding the sub-horizontal stratification, four main sets can be identified on the rock mass underlying Mdina.

Four discontinuity sets have also been identified within the rock slab underlying Citadel (Fig. 8b).

Both sites show medium pole dispersion, with a prevalence of high dipping discontinuity planes (excluding the bedding planes).

These structural data were employed in the kinematic analyses and numerical modelling, described in Sect. 4.

The shear strength of discontinuities was calculated using Barton's failure criterion (Barton and Choubey, 1977). Finally, for a complete characterization of the material properties to be used in the numerical model, the Mohr Coulomb equivalent strength parameters of the rock mass were calculated through the Hoek and Brown failure criterion (Hoek and Brown, 1980; Hoek et al., 2002). These properties were used as input parameters for the kinematic analyses and numerical modelling (Table 1).

3.3 Laser scanning survey

Nowadays, advanced techniques are available for obtaining high resolution 3-D representations of land surface, such as digital photogrammetry (Chandler, 1999; Lane et al., 2000) and laser scanning (both terrestrial and aerial) (Kraus and Pfeiffer, 1998; Frohlich and Mettenleiter, 2004).

The main product of a long range laser scanning survey is a high resolution point cloud, obtained by measuring with high accuracy (millimeter or centimeter) the distance of a mesh of points on the object, following a regular pattern with polar coordinates. The high acquisition rate (up to hundreds of thousands points per second) makes the detailed 3-D shape of the object immediately available.

The advantage of employing remote and high resolution surveying techniques is that it allows us to perform detailed analyses and to rapidly obtain information on inaccessible rock exposures. This is very important in the field of engineering geology and emergency management, when it is

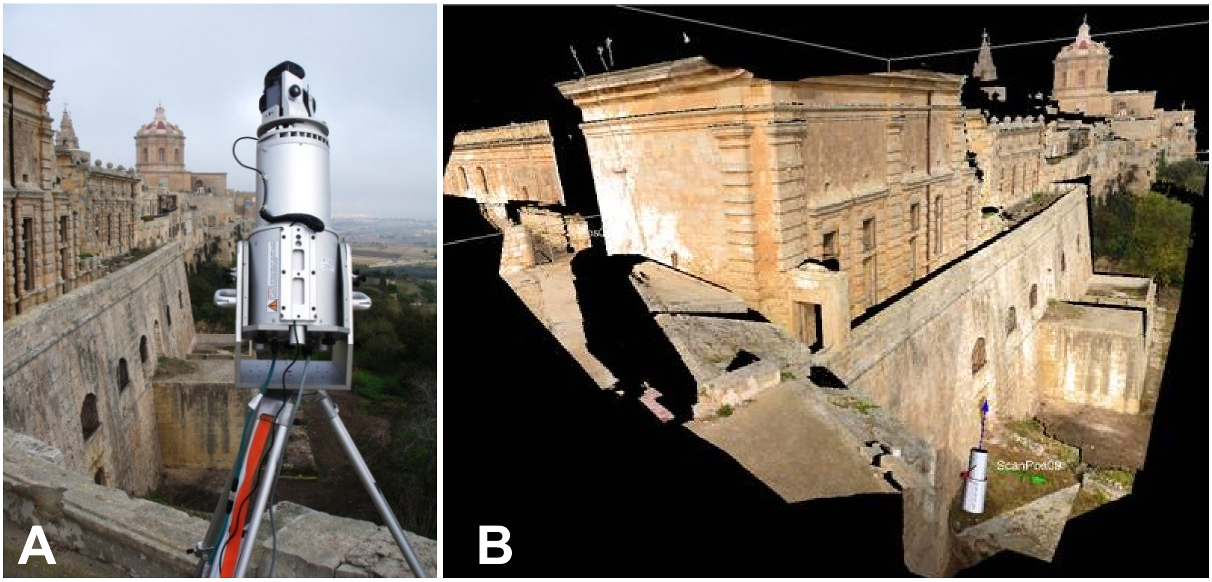

Fig. 9. Laser scanner in action at Vilhena Palace, Mdina**(A)**; True coloured 3-D point cloud of Vilhena Palace, Mdina**(B)**.

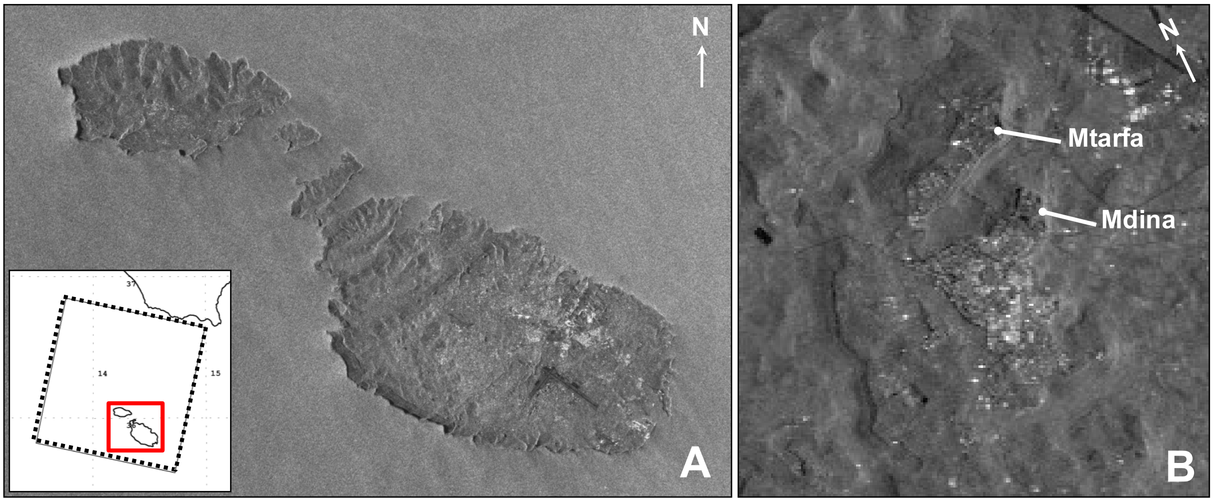

Fig. 10. **(A)**: Example of ERS2 image acquired along descending orbit on the Maltese Archipelago (displayed in terms of amplitude). Footprint of the whole scene is shown within the inset as a dashed black polygon. **(B)**: Subset of **(A)** displayed in SAR coordinates and including the urban area of Mtarfa and Mdina.

often advisable to minimize survey time in dangerous environments and at the same time gather all the required information as fast as possible.

The Laser Scanning technique is being more frequently used for instability analyses in cultural heritage sites (Boehler et al., 2001; Arayici, 2007; Lambers et al., 2007; Yastikli, 2007; Yilmaz et al., 2007; Al-kheder et al., 2009; Fanti et al., 2011, 2012), as it allows detailed and high accuracy 3-D representation of both the underlying ground and the overlying structures in a short time.

A detailed 3-D model of the investigated sites is useful for building a complete digital model including the structures and the slopes, making it possible to reconstruct the plano-altimetric relationship between the local geology and the man-made structures (Figs. 6 and 7). Thanks to the high resolution of the laser scanning survey we can also extract even the smallest features, such as the structural crack pattern, the crack opening direction (Gigli et al., 2009), and the orientation of critical discontinuities within the rock mass (Gigli and Casagli, 2011).

A laser scanning survey of the investigated Mdina areas was carried out, by employing a long range 3-D laser scanner (RIEGL LMSZ410-i) (Fig. 9a). This device can determine the position of up to 12 000 points s^{-1} with a maximum

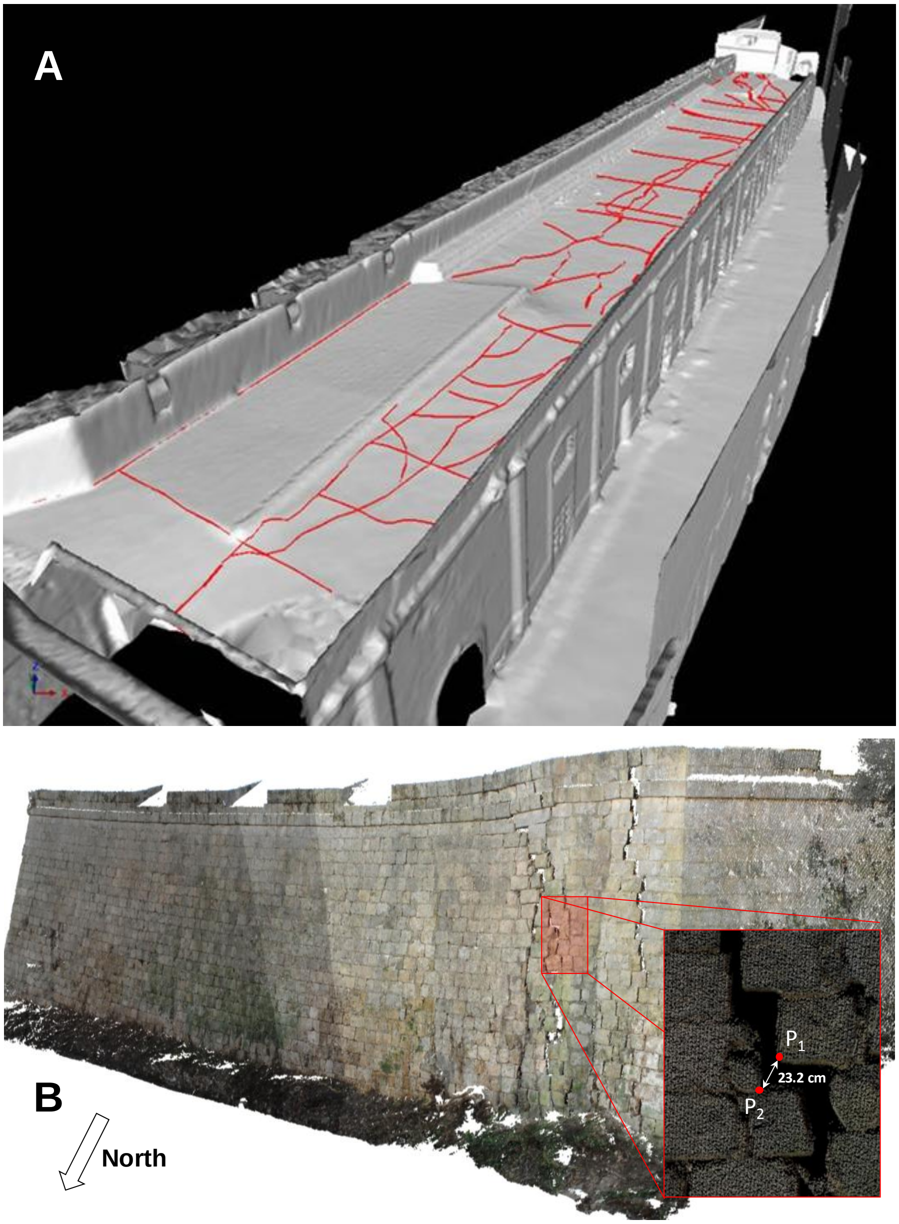

Fig. 11. (A): 3-D polylines of the main cracks affecting the Curtain Magazines. **(B)**: True coloured point cloud and displacement vector of a crack affecting the Despuig Bastion (modified from Gigli et al., 2009).

angular resolution of 0.008° and an accuracy of ±10 mm from a maximum distance of 800 m. In order to completely cover the intervention areas, several surveys from different scan positions were performed. The different point clouds were subsequently linked to a projection reference system with the aid of reference points, whose coordinates were defined by using a differential GPS. Three different projects were constructed, corresponding to the number of the study areas.

Area A was covered by 26 different scan positions, and areas B and C by 12 and 18 scan positions respectively. A total of more than 200 million points and 250 high resolution digital images were taken.

All the acquired point clouds were cleared of vegetation and encumbering objects, and were given their true colours acquired by a high resolution digital camera mounted over the instrument (Fig. 9b). For each study area all point clouds were linked, based on a global reference system, and a continuous surface was created by triangulation points from discrete point clouds.

As regards Citadel, the 3-D model employed for the kinematic analysis and the numerical modelling, produced by

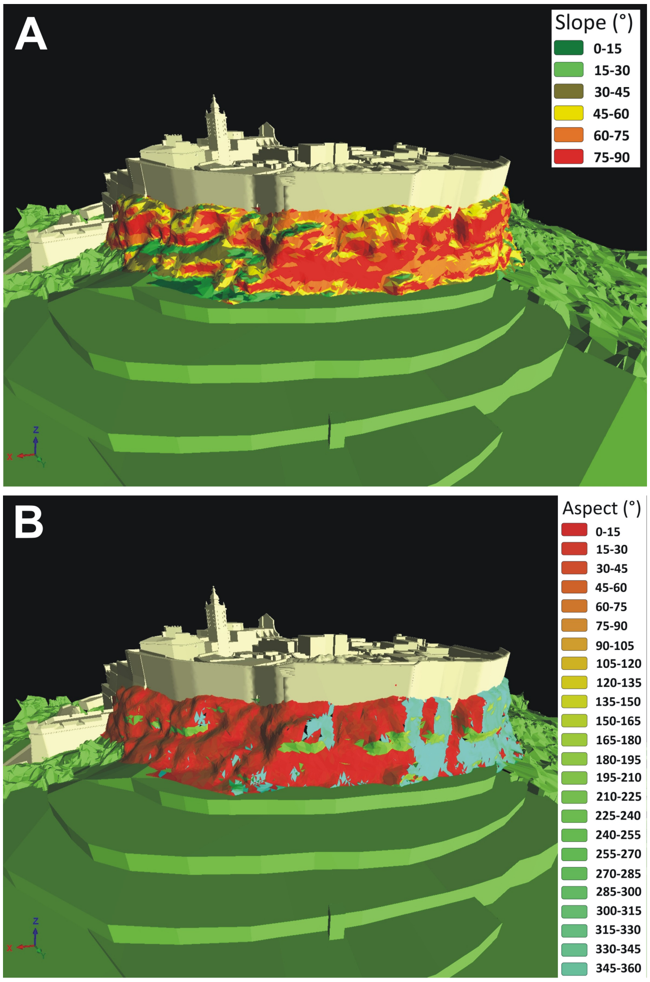

Fig. 12. 3-D maps of slope steepness **(A)** and aspect **(B)** of the Citadel rock mass.

the "Consorzio Ferrara Ricerche of the University of Ferrara", under the Service Tender for the documentation of the Citadel Fortifications, was provided by the Restoration Unit, Works Division, Floriana (Malta) within the Ministry for Resources and Rural Affairs.

3.4 Satellite radar data (1992–2001)

In situ investigations carried out at Mdina were completed with satellite radar monitoring by means of Persistent Scatterers Interferometry (PSI). Developed in the late '90s, this remote sensing technique uses long temporal series of Synthetic Aperture Radar (SAR) imagery allowing for the recognition of reflective targets on the ground, which makes possible the detection and monitoring of the displacements occurring between the analysed satellite acquisitions (Ferretti et al., 2001; Crosetto et al., 2010). Thanks to wide area coverage, millimeter precision and cost-effectiveness, PSI technologies can successfully integrate conventional field investigations in the reconstruction of the past deformation history of the observed areas, and improve the understanding of the deformation mechanisms threatening unstable structures and infrastructures (Casagli et al., 2009; Cigna et al., 2010, 2011; Righini et al., 2011).

The multi-temporal PSI analysis in Mdina was used to test the feasibility of radar remote sensing for the analysis of the instability mechanisms affecting the rock plate-soft substratum system. The measurement of land displacements induced by hydrogeological and structural instability often represents the most effective method for the definition of the hazard and risk scenarios, the choice of corrective actions aimed at risk reduction and/or the evaluation of their effectiveness.

The availability of historical datasets of ERS1/2 radar images made possible the retrospective analysis of past movements occurring in Mdina since the early '90s. Launched and operated by the European Space Agency (ESA), the ERS1/2 satellites were the first radar missions acquiring commercially available microwave data since July 1991 (ERS1) and May 1995 (ERS2). To perform the PSI analysis, a data stack of 63 ERS1/2 scenes acquired along descending orbits in the period 5 June 1992 – 8 January 2001, with nominal revisiting time of 35 days, was selected.

These images were acquired in C band (wavelength of 5.66 cm) and VV polarization, and are characterized by a resolution of about 20 m on the ground and a spatial coverage of 100 km by 100 km, consequently covering the whole archipelago (Fig. 10). At the analysed latitudes, the Line Of Sight of the ERS1/2 satellites in the descending mode has an azimuth of about 257° and a look angle of 23° (measured from the vertical direction).

4 Data analysis

4.1 Quantitative deformation analysis affecting Mdina structures

The high detail of the laser scanning point clouds, integrated with the high resolution digital images acquired by the camera mounted over the device, allowed for the construction of a 3-D map of the main fractures affecting Mdina structures, by digitizing 3-D polylines over the crack traces (Fig. 11a). Displacement vectors were calculated for the main cracks or deformed structures, with the aim of identifying the structural deformation patterns. Each vector was drawn by joining two corresponding points selected from the 3-D point cloud. These were chosen because they occupied the same location before displacement had occurred (Fig. 11b).

4.2 Kinematic analysis

The term kinematic refers to the study of movement, without reference to the forces that produce it. This kind of analysis is able to establish when a particular instability mechanism is kinematically feasible, given the geometry of the slope and discontinuities.

The main instability mechanisms investigated with this approach are:

- plane failure (PF) (Hoek and Bray, 1981);
- wedge failure (WF) (Hoek and Bray, 1981);
- block toppling (BT) (Goodman and Bray, 1976; Matheson, 1983);
- flexural toppling (FT) (Goodman and Bray, 1976; Hudson and Harrison, 1997).

Casagli and Pini (1993) introduced a "kinematic hazard index" for each instability mechanism. These values are calculated by counting poles and discontinuities falling in critical areas:

N_{pf} = number of poles satisfying plane failure conditions;
I_{wf} = number of intersections satisfying wedge failure conditions;
N_{bt} = number of poles satisfying block toppling conditions;
I_{bt} = number of intersections satisfying block toppling conditions;
N_{ft} = number of poles satisfying flexural toppling conditions.

The kinematical hazard index is calculated as follows:

$C_{\mathrm{pf}} = 100 \times (N_{\mathrm{pf}}/N)$ for plane failure;
$C_{\mathrm{wf}} = 100 \times (I_{\mathrm{wf}}/I)$ for wedge failure;
$C_{\mathrm{bt}} = 100 \times (N_{\mathrm{bt}}/N) \times (I_{\mathrm{bt}}/I)$ for block toppling;
$C_{\mathrm{ft}} = 100 \times (N_{\mathrm{ft}}/N)$ for flexural toppling.

Where N and I are the total number of poles and intersections respectively.

By using specific software, such as KARS (Casagli and Pini, 1993), or Rock Slope Stability (Lombardi, 2007) it is possible to load a great number of discontinuities with different friction angles.

Intersection lines are calculated automatically, together with the equivalent friction angle, based on the friction angles of the intersecting planes and the shape of the wedge (Casagli and Pini, 1993).

The analysis can be performed for specific slope orientations, or for each cell of a 3-D surface (true 3-D kinematic analysis).

4.2.1 3-D kinematic analysis – Citadel

The Citadel rock mass is characterized by different joint sets (Fig. 8b; Table 1).

As the orientation of these fractures does not seem to be random, but related to the tectonic processes that have been acting in the investigated area, a kinematic analysis can be useful to highlight the rock wall sectors which are more prone to instability processes. These are identified by combining fracture dip and dip directions with local slope orientations.

The rock plate is, in fact, characterised by very steep slopes, sometimes overhanging, and, due to its circular shape, by the whole range of possible slope aspects.

Local slope orientation data were evaluated by analysing the 3-D model produced by the "Consorzio Ferrara Ricerche of the University of Ferrara", under the "Service Tender for the documentation of the Citadel Fortifications, Gozo, Malta".

It is important to point out that this analysis only takes into account those discontinuities intersected by the scanline geomechanical surveys carried out at the base of the cliff, and does not consider minor and irregular fractures originating in local stress concentrations, thus underestimating the probability of occurrence of instability phenomena in those areas.

The analysis input parameters are the slope dip (Fig. 12a), the dip direction (Fig. 12b), and the discontinuity surface orientations.

The analyses were performed by applying the method proposed by Lombardi (2007), which employs the principles of kinematic analysis to overhanging slopes.

The discontinuity shear strength was considered purely frictional, and the mean peak friction angle resulting from the analysis of geomechanical data was set to $\phi = 48°$.

The results of the analysis for each mechanism investigated are presented in Fig. 13.

The kinematic indices were plotted with a common legend, scaled according to the maximum values (30 %).

4.2.2 Constant dip kinematic analysis – Mdina

By observing the fracture distribution on the structures in the Mdina area, we can say that these are mainly caused by differential movements, due to different mechanical characteristics of the underlying materials.

In addition, rigid block displacements along pre-existing rock mass discontinuity planes can occur. In fact, the shear resistance of discontinuities is much lower than the intact rock strength.

Thus, the presence of unfavourably oriented discontinuity sets would enhance deformational mechanisms on the rock slab, leading to major fractures in the overlying buildings and bastions.

To quantify this behaviour of the UCL rock mass, we can make use of kinematic analysis principles. Although kinematic analysis applies to sub-aerial slopes, we can employ this concept to a buried rock plate, such as the rock mass underlying the town of Mdina.

The aim of this study is to demonstrate that damage to buildings and ground displacements observed in the study areas are amplified by the presence of unfavourably oriented discontinuity sets, dissecting the UCL plate.

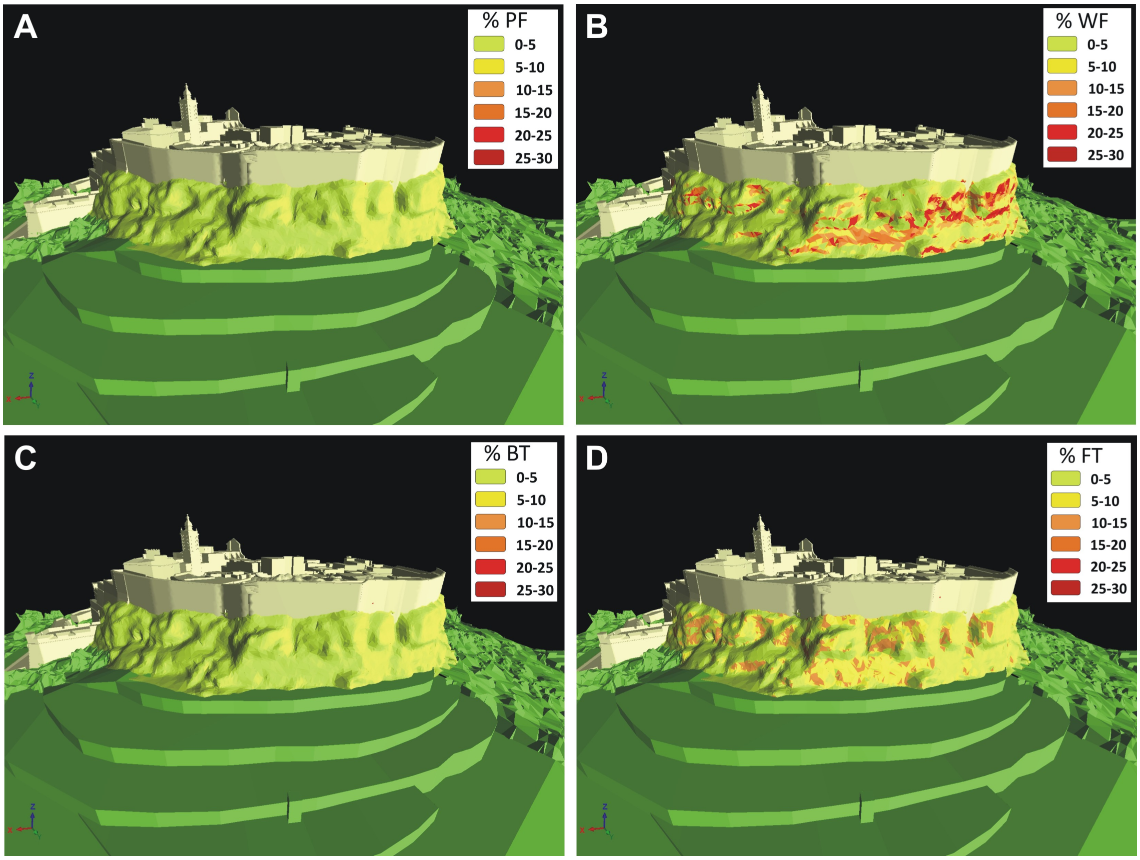

Fig. 13. 3-D maps derived from the results of the kinematic analysis for the northern sector of Citadel rock mass. **(A)**: Plane failure (PF); **(B)**: wedge failure (WF); **(C)**: block toppling (BT); **(D)**: flexural toppling (FT).

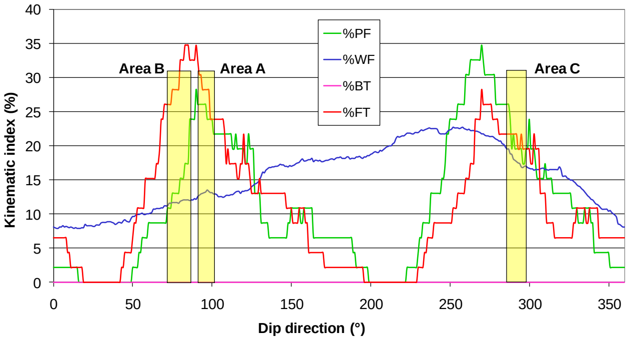

Fig. 14. Constant dip quantitative kinematic analysis for Mdina. Yellow rectangles indicate the dip direction range for each investigated area. (PF: plane failure; WF: wedge failure; BT: block toppling; FT: flexural toppling).

The employed quantitative approach considers a fixed slope dip (80°); the kinematic hazard index for each instability mechanism is then calculated by varying the slope dip direction from 0° to 360°. Given a certain slope dip, it is therefore possible to identify the most unfavourable slope orientations for the main instability mechanisms.

The results of the analysis are presented in Fig. 14, where the kinematic indices are plotted for each slope dip direction; yellow rectangles indicate the dip direction range for each study area.

4.3 Numerical modelling

The identified instability processes were also investigated by means of numerical modelling.

This analysis was performed for the Citadel slopes by employing the Universal Distinct Element Code (UDEC, Itasca, 2004). This is a two-dimensional numerical program based on the Distinct Element method for discontinuum modelling, which simulates the response of discontinuous media (such as a jointed rock mass) subjected to either static or dynamic loading. The discontinuous medium is represented as an assemblage of discrete blocks, and discontinuities are treated as boundary conditions between blocks; large displacements along discontinuities and rotation of blocks are allowed. Individual blocks behave as either rigid or deformable material.

Deformable blocks are subdivided into a mesh of finite-difference elements, and each element responds according to a prescribed linear or non-linear stress-strain law. UDEC

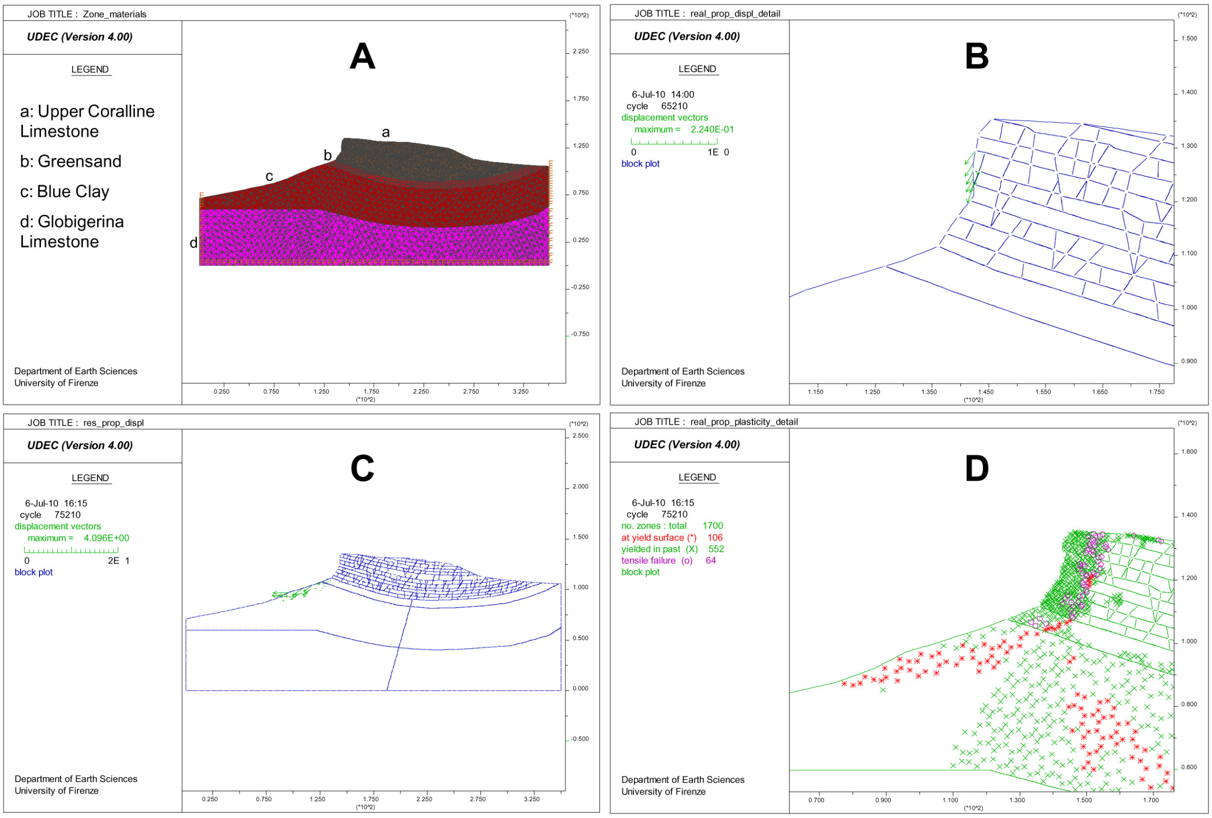

Fig. 15. Numerical modelling results. **(A)**: Initial model; **(B)**: Block displacements (third step); **(C)**: Displacement vectors (fourth step); **(D)**: Zone state (fourth step).

is based on a “Lagrangian” calculation scheme that is well-suited to model the large movements and deformations of a blocky system, such as the one investigated.

The analysis was performed along the profile shown in Fig. 7. This section was chosen due to the local steepness of the rock wall, which is affected by several instability mechanisms.

Fractures were generated within the UCL layer, according to the apparent orientation of the discontinuities surveyed (Fig. 15a). Each block was subdivided into a mesh of finite-difference elements, and each element was assigned a Mohr Coulomb constitutive model.

Joints were assigned the Coulomb slip criterion, which gives elastic stiffness, frictional, cohesive and tensile strengths, and dilation characteristics to each joint. Both the material and the joint properties were selected based on the results of the geomechanical survey (Table 1).

The first step of the analysis consists in the setting up of the stress state. This was performed by assigning high strength to materials and discontinuities together with real elastic properties, thus allowing the model to converge to equilibrium under its own weight. After assigning real peak strength properties to zones and joints (second step), the model still converged to a stable state, but with some plastic deformations below the rock plate, probably because in situ BC strength parameters are higher than the simulated ones.

The third step of the numerical modelling consists in assigning joint residual properties, in order to simulate shallow instability phenomena induced by weathering processes. With these perturbations the model did not reach equilibrium, and blocks delimited by steep joints that dip out of the cliff face moved downward, especially in sections corresponding to overhanging parts (Fig. 15b).

For the last stage (fourth step), falling blocks were removed, to restore the model to a stable state, and residual strength properties were assigned to the shallow part of the BC region, in order to simulate the eventual processes of decay of these materials, favoured by the poor conditions of the Citadel retaining terrace walls. Due to this modification, a shallow landslide is triggered in the numerical model (Fig. 15c), and mixed shear-traction sub-vertical fractures are induced throughout the whole upper rock plate by the resulting undermining action (Fig. 15d).

4.4 Persistent Scatterers analysis

The PSI processing approach implemented in Mdina is the Interferometric Point Target Analysis (IPTA), developed by

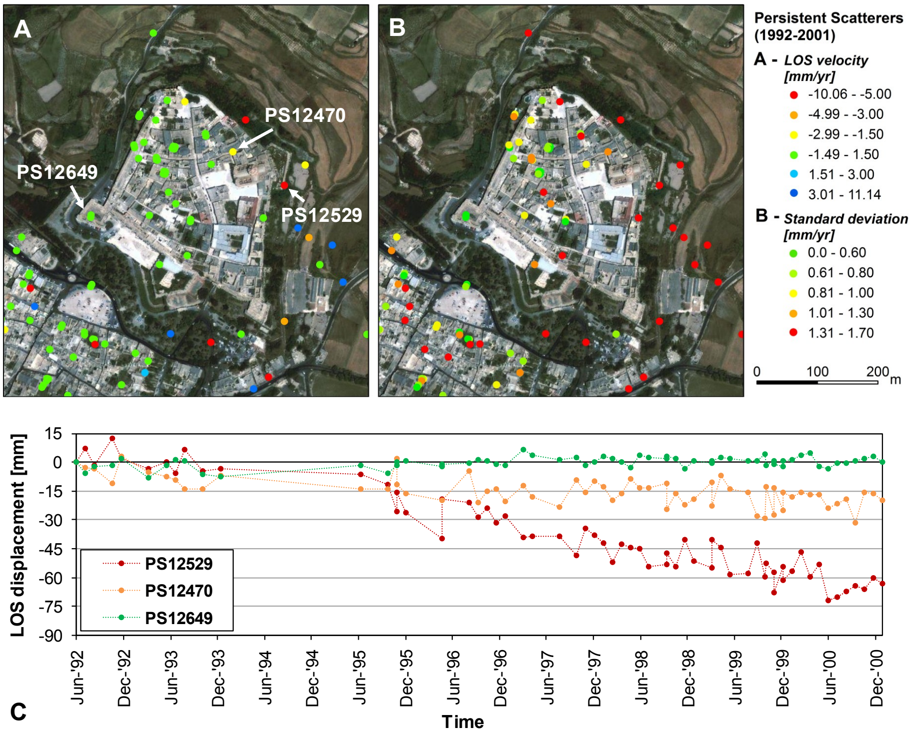

Fig. 16. (A): LOS displacement velocities measured between 1992–2001 for the ERS1/2 Persistent Scatterers identified in the area of Mdina. Negative velocities indicate movements away from the sensors, while positive values indicate movements toward the sensor. **(B)** Standard deviations of LOS velocity of the identified PS. **(C)**: Deformation time series of selected PS. For graphical purposes, the temporal reference for the time series was shifted from the master images (30 March 1998) to the first SAR acquisition (5 June 1992).

Gamma Remote Sensing and Consulting AG, Switzerland. The interferometric phase model used by IPTA is the same as that used in conventional interferometry, and can be expressed as the sum of topographic, deformational, differential path delay (i.e. atmospheric), and noise phase components (Werner et al., 2003). Through the use of point targets (the so called PS, Persistent Scatterers), interferometric pairs with longer baselines can also be used (even above the critical baseline), increasing the number of scenes processed, allowing a reliable removal of the atmospheric components, and leading to both a better temporal coverage and a more precise estimation of ground displacements.

Within each ERS1/2 scene, a 9 km by 9 km working area including the towns of Mdina, Mtarfa, Mosta and Siggiewi was selected, and the processing started with the coregistration of the full stack of images to a single master (i.e. the 30 March 1998 scene). A 90 m resolution Digital Elevation Model (DEM) obtained through the SRTM (Shuttle Radar Topography Mission) mission was used to simulate the topographic phase component (Werner, 2001). Criteria for the selection of PS candidates included low temporal variability of the backscattering coefficient and also low spectral phase diversity, to maximize the density of the PS candidate network. The presence of point targets depended strongly on the scene and many points were identified in built-up areas (e.g. man-made structures, buildings, antennas), while very few points were detected in vegetated and agricultural areas.

A simple linear model of phase variation through time was chosen to extract the components related to ground displacements; linear variability of the topographic phase on the perpendicular baseline was also taken into account. Each PS phase model was improved through a step-wise iterative processing, using height corrections (added to DEM heights), linear deformation rates, standard deviations from regression, and residual phases (including atmospheric, nonlinear deformation and error terms), to progressively update the different phase components. Final results of the IPTA processing include a set of 10 941 point targets (average density of 140 PS km^{-2}), characterized by information on height, yearly deformation velocity measured along the satellite LOS (Line Of Sight), quality information (standard deviation of LOS velocity), and non-linear deformation history with millimeter precision (Fig. 16).

5 Discussion

On the basis of the undertaken surveys and analyses, specific instability processes can be inferred for the two investigated sites. Some differences however arise, mainly due

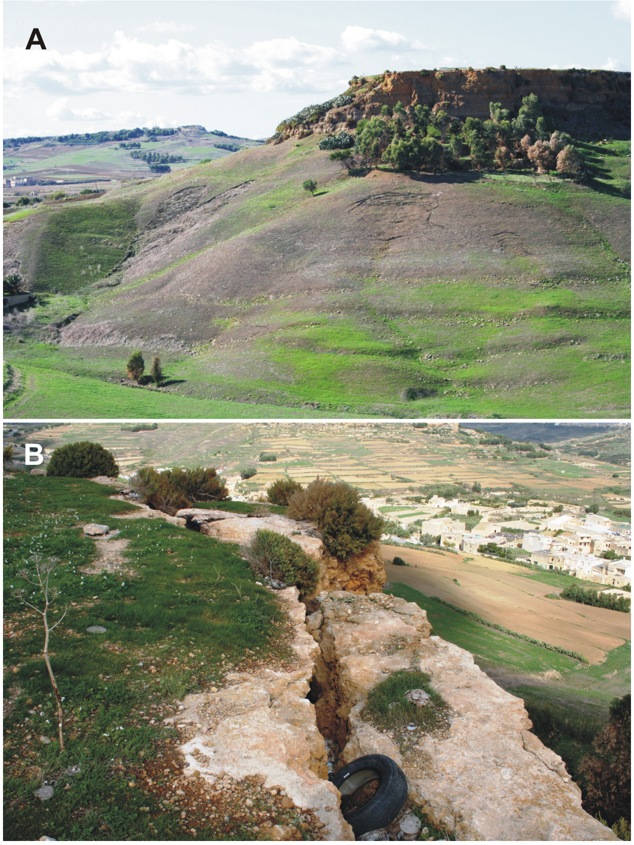

Fig. 17. Field validation of the numerical modelling results. **(A)**: General view of the Gelmus Hill, close to Citadel; **(B)**: Detail of the outer portion of the rock mass.

to the major thickness and different structural setting of the rock plate underlying Citadel.

For this reason, and given the intense urbanization of the Mdina site, the effects of these mechanisms of instability, are more evident in the rock mass outcropping at Citadel and the anthropic structures built on the margin of the Mdina cliff face.

The sub-vertical rock wall of Citadel is, in fact, heavily prone to rockfall, as results from both the 3-D kinematic analysis and the numerical modelling. This is a very important point, as the touristic appeal of the site can result in high risk levels, especially in case of exploitation of the area under the cliff for the construction of a pedestrian path.

Figure 13 shows that the mechanism associated to the highest index is wedge failure (WF max = 30 %), followed by flexural toppling (FT max = 17 %). All the other mechanisms seem to be irrelevant, due to the fact that the bedding planes always dip gently into the slope. All the northern sector is currently deeply affected by wedge failure, especially where the formation of wedges is favoured by the cliff overhanging parts, as confirmed from field evidence, which shows signs of a number of niches and potential wedge detachments.

The numerical modeling, besides confirming these superficial instability mechanisms, also displays the possibility of a deeper involvement of the rock mass, in case of shallow landslide or undercutting within the underlying clayey unit (Fig. 15d). Such phenomena are clearly visible on the boundary of the UCL rock plate at Gelmus Hill, near Citadel (Fig. 17), where the clay slopes are not terraced, and shallow landslides can take place. The distance from the cliff face of the observed fractures seems however slightly lower than that of the numerical modelling, probably due to a low spatial resolution of the model caused by a coarse meshing. These kind of processes, however, do not seem to be presently affecting the Citadel rock plate, where the instability phenomena are mainly constituted by rockfalls along pre-existing structural discontinuities; the latter are enhanced by the intense weathering conditions of the rock walls. Probably this is due to the concave setting of the hill (Fig. 7), caused by the solution collapse structure, which prevents the concentration of high stress at the base of the cliff, thus limiting plastic deformations.

As regards Mdina, the integration of geological, geomorphological and geomechanical surveys with the 3-D distribution of fractures, the quantitative displacement analysis of the structures, and the Persistent Scatterers study allowed us to understand the basic kinematic behaviour in the study area.

The bastion and buildings in the investigated areas were built in different periods and are founded both on the cap rock and on the clayey unit. The damage to the bastions and buildings is, therefore, mainly associated to differential movements produced by the contrasting mechanical behaviour of the underlying materials or by rock block displacements. In fact the UCL rock mass is here quite thin; this leads to rock fragmentation, located mainly along the rock plate borders.

The Vilhena Palace area (Area A) shows the most complex fracture pattern, probably due to the thin and heavily fractured underlying rock mass, and the intrinsic structural problems linked to the different construction phases (Fig. 6). In the Cathedral area (Area B), a predominant translational displacement with an E-SE direction is associated with considerable vertical component. This behaviour is in accordance with the geological setting, as the Despuig bastion was constructed directly on the stratigraphic contact between the UCL and the BC (Fig. 6). The Curtain Magazine area (Area C) is characterized by an intense concentration of fractures, most of which show displacement vectors with a sub-horizontal direction and apertures of up to 20 cm (Fig. 11a). These displacements are compatible with the differential behaviour of the materials underlying the structure, and can be emphasized by the presence of a relevant ancient landslide, which is probably responsible for the local rock plate indentation (Fig. 6). All the instability processes within the investigated areas are also magnified by the presence of unfavourably orientated discontinuity sets with respect to the main instability mechanisms affecting the rock mass (Fig. 8A). The constant dip kinematic analysis (Fig. 14) confirms that all the study areas are oriented unfavourably with respect to all the mechanisms analysed (with the exception of block toppling), with high kinematic hazard indices (ranging from 12 % to 35 %).

It is important to stress that, for the investigated sites, the instability of both the cliff and the overlying structures is also greatly affected by presence of the BC Formation underlying the limestone cap rock, which can be subjected to flow phenomena or volume variations caused by the seasonal changes of water content. Clayey hillslopes have long been used intensively for agricultural purposes; at present, these slopes (especially at Citadel) are only marginally used for agriculture, while most of the area is uncultivated. Terraces are still evident, but the retaining walls show the traces of long-standing neglect (Scerri, 2003).

The buildings and bastion walls, being made of local stone (UCL or GL), are also affected by weathering and alteration patterns that can be observed on single stones, mainly due to thermal expansion, haloclasty and wind action.

PSI processing of the available SAR images covering the area of Mdina allowed us to improve the knowledge about the instability affecting the different sectors of the walled city and to detect its spatial distribution and temporal evolution. The results of the IPTA processing indicate a general stability over the whole area between 1992 and 2001. In the inner sectors of Mdina, only 38 PS are identified and most of them show null to very low annual deformation velocities (i.e. lower than ±1.5 mm yr), as well as a quite stable displacement history over the whole time interval (Fig. 16). The identified targets are not homogeneously distributed over the city. They lack especially in the areas of Vilhena Palace, Cathedral and Despuig Bastion, and Curtain Magazine, where the severest damage occurred. Some unstable targets are detected in the eastern and north-eastern sectors of the walled city. In particular, a target located on the Despuig Bastion (PS12529) shows a significant rate of deformation of about $-8.6\,\mathrm{mm\,yr^{-1}}$, measured in the LOS direction (Fig. 16a). However, values of standard deviation of the measured velocity of this specific target and many other identified targets are quite high (up to $1.7\,\mathrm{mm\,yr^{-1}}$), due to the presence of noise and significant phase components deviating from the assumed linear model of deformation (Fig. 16b).

6 Conclusions

This paper deals with the geological and geomechanical study of the rock plate – soft substratum system on which Mdina (island of Malta) and Citadel (island of Gozo) are built.

The geological setting of the investigated sites is dominated by the superimposition of a stiff and brittle limestone plate, belonging to the Upper Limestone Formation, on a clayey unit (Blue Clay Formation). The selective action of erosion affects mainly the more erodible substratum; therefore the rock masses investigated constitute buttes higher than the surrounding countryside, bordered by steep cliffs.

Several field activities were carried out, together with laboratory tests, kinematic analyses, numerical modelling, and a Persistent Scatterers study over the period 1992-2001, with the aim of characterising the material properties and the main instability processes acting on the cliff face and the underlying hillslopes.

Based on these studies, the following conclusions can be drawn. The sites investigated show instability processes that are peculiar to rock masses overlying soft-substratum systems. The geomorphological differences are mainly related to the rock plate thickness and structural setting, giving rise to different instability mechanisms for the two sites investigated. The maximum probable scenario at Citadel is related to the detachment of rock wedges along pre-existing joints, which, due to the sub-vertical cliff, are able to reach long run-out distances by bouncing and rolling along the hillslopes. The process is ongoing, since once a block has been detached, the relaxation of pressure on the newly exposed cliff face results in the gradual development of a new joint system (Scerri, 2003).

Three areas located in Mdina are more affected by instability processes. These are mainly concentrated in locations where the intense urbanization has led to structures being built over the contact between the limestone rock mass and the underlying clayey unit. The geomechanical and kinematic analyses also showed that in these areas the discontinuity sets are unfavourably orientated with respect to the main instability mechanisms. The hypothesis that this setting could enhance deformational mechanisms on the UCL slab, leading to major cracks in the overlying buildings and bastions, is thus suggested.

All the identified processes are favoured by possible instability processes affecting the underlying clayey slopes, which are able to influence the rock plate shape and trigger large sub-vertical fractures in the overlying UCL Formation. On the basis of this evidence, a specific monitoring system has been installed and appropriate consolidation interventions are being designed.

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