Integrated Monitoring of Lateral Spreading Phenomena Along the North-West Coast of the Island of Malta

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Abstract

Landslides, and especially lateral spreading, are responsible for the main landforms observable along the north-western coast of the Island of Malta. A series of rock spreading phenomena, and associated mass movements, have been recognised in this area and the most significant cases have been investigated by means of a multi-technical approach which envisaged geomorphological survey and mapping, geophysical analyses and monitoring of displacements. The aim of the study was to define whether rock spreading phenomena are active along the investigated coastal stretch and, possibly, to determine the rate of movement of the most relevant cases. In this framework, a multidisciplinary approach was used and different techniques were tested and applied on a specific site, which was selected for the presence of an extensive rock spread phenomenon which may induce hazard conditions. The site is located at Il-Prajjet (Anchor Bay), a narrow inlet where a tourist attraction is located. Research activities have been carried out at Il-Prajjet since 2006 when a GPS network of eight benchmarks was installed. This technique was chosen because it proved to be a powerful tool in the study of similar ground deformation in coastal and mountain areas, showing high accuracy and reliability. Once GPS monitoring had showed that rock spreading was active, further techniques were applied in order to achieve an in-depth knowledge of the instability processes occurring at Il-Prajjet. The paper illustrates the results so far achieved thanks to GPS monitoring, tape extensometer measurements, SAR interferometric analyses and GPR investigations.

Keywords

Coastal instability • Rock spreading • GPS • SAR interferometry • GPR • Malta

Introduction

The investigation of landslides is sometimes limited to a purely descriptive approach without quantitative assessments and continuous monitoring. This is especially the case of very slow mass movements, such as rock spreading (cf. Pasuto and Soldati 1996). These phenomena are rarely monitored over long periods, though this is, in most cases, the only way to achieve enough data to properly understand their kinematics and triggering mechanisms (e.g., Guerricchio et al. 1988; Vlcko 2004; Prokop and Panholzer 2009; Lissak et al. 2010).

In these situations, monitoring techniques have become a powerful tool in landslide analyses due to the high accuracy

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C. Margottini et al. (eds.), *Landslide Science and Practice*, Vol. 2,
DOI 10.1007/978-3-642-31445-2_30,

Fig. 1 Panoramic view of the north side of Anchor Bay (north-west coast of Malta)

and reliability that recent instrumentation provides (Dunnicliff 1995; Angeli et al. 2000; Corominas et al. 2000; Malet et al. 2002; Corsini et al. 2005; Petley et al. 2005; Lissak et al. 2010).

Nevertheless, long-term monitoring of rock spreading phenomena is still quite rare due to the fact that this type of mass movement normally is not considered as hazardous, due to the slow rate of movement. Nevertheless, it should be emphasized that rock spreading, can be highly hazardous for engineering structures or buildings, since it may act over wide areas, during long periods of time and involving large volumes of rock masses. Moreover, these phenomena can evolve into faster movements, which can determine catastrophic failures (i.e. block slides) or they can favour and trigger a series of collateral landslides (i.e. block slides, rock falls and topples, rotational slides, earth slides and flows) occurring at the edges of the areas affected by spreading (Pasuto and Soldati 1996; Pasuto et al. 1997).

In this context, the coupling of conventional monitoring techniques (e.g., topographic and extensometric measurements) with innovative ones (e.g., ground-based GPS or satellite SAR interferometric analysis) make up a reliable solution to detect and survey active deformation due to rock spreading, with promising perspectives in terms of hazard assessment and possible mitigation actions.

Research activities have been carried out in the frame of a co-operation programme between the University of Modena and Reggio Emilia (Italy), the Italian National Research Council (CNR), the University of Malta, the University of Trieste (Italy) and the University of Cantabria (Spain) which also included the mobility of young researchers. The objectives of the research, which is still in progress, are pursued through multidisciplinary investigations which foresee an integrated geomorphological and engineering-geological approach.

The attention has been focused along the north-western coast of the Island of Malta (central Mediterranean Sea) where exemplary cases of lateral spreading phenomena are found (Magri et al. 2007, 2008; Magri 2009). The latter develop because of the superimposition of rock types having very different mechanical behaviour (limestones over clayey terrains).

In particular, extensive rock spreading phenomena have been recognized, mapped and monitored at Il-Prajjet (Anchor Bay), with the aim of assessing the hazard conditions of one of the main tourist attractions of the Maltese Islands, an amusement park which was developed in the early 1980s (Fig. 1).

Physical Setting of the Study Area

The study site is located at Il-Prajjet (Anchor Bay) which is a narrow inlet along the north-western coast of the Island of Malta (Fig. 2), and in particular along its north side (Said and Schembri 2010). This sector of the bay is characterised in its upper portion by a 20–30 m high escarpment, which runs in an E-W direction (Fig. 3).

The origin of the bay is clearly linked to the presence of two faults (WSW-ENE oriented) which follow the general tectonic trend of the area (Pedley et al. 2002) (Fig. 3).

From a geological point of view, the northern part of the bay is characterised by the outcrop of terrains belonging to the Blue Clay Formation (at the base) and to the Upper Coralline Limestone Formation (at the top), the latter making up the younger rock units of the Maltese stratigraphic sequence (Pedley et al. 1978, 2002). The limestones give rise to a wide karst plateau bounded toward the sea by steep cliffs, whereas the Blue Clays outcrop near the sea level, often covered by limestone blocks and debris accumulations (Fig. 4).

The *Upper Coralline Limestone Formation* (Upper Miocene) covers the above mentioned stratigraphic unit giving rise to vertical cliffs of varying heights along the coastline, up to over 30 m. It is mainly composed by shallow marine sediments, making up hard limestones affected by a dense

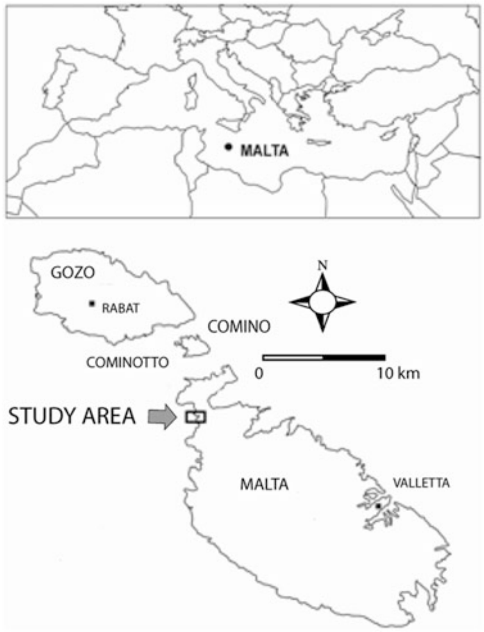

Fig. 2 The location of Il-Prajjet (Anchor Bay) within the Maltese archipelago

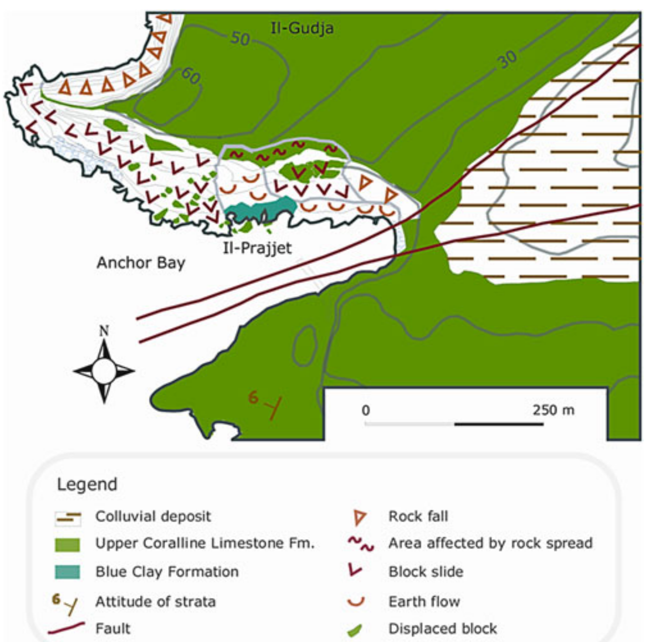

Fig. 3 Geomorphological sketch map of the study area. The map clearly shows the extensive landslide accumulations, which characterise the northern part of the bay

network of joints which provides the rock masses with a brittle behaviour.

The *Blue Clay Formation* (Middle Miocene) can reach a thickness of 65 m in the Maltese archipelago and is composed by silty sands, marls and clays showing poor

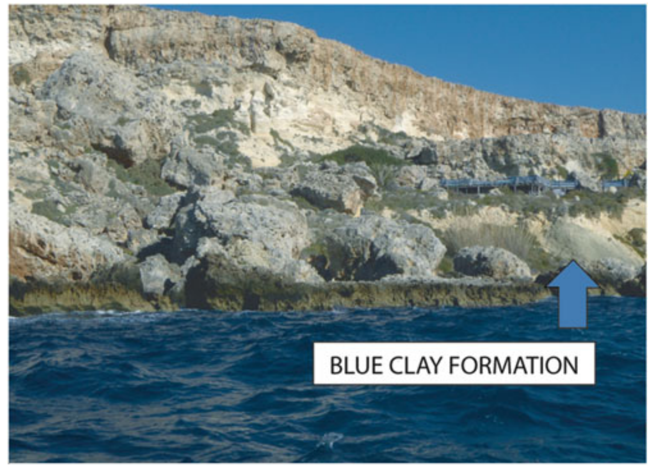

Fig. 4 The northern sector of Anchor Bay, where the Upper Coralline Limestone Formation is characterised by steep cliffs and the Blue Clay Formation outcrops near the sea level

Fig. 5 The rock blocks detached from the limestone plateau, as a result of block sliding, determine a hazard conditions for the tourist infrastructure located beneath

geotechnical properties which favour the onest of slope movements including the spreading of the overlying limestones.

The different mechanical behaviour of the Blue Clay and the Upper Coralline Limestone formations favours the development of a peculiar rock spreading phenomenon at Il-Prajjet which has evolved into a large block slide (Magri et al. 2008; Magri 2009) (Fig. 5). Also the different hydrogeological properties of the two formations mentioned above have to be considered, since a karst aquifer may be formed just above their contact surface (Mangion 1991). The evolution of this complex coastal instability phenomenon may induce hazard conditions to the tourist infrastructure located between the coastline and the foot of the block slide, for the assessment of which the understanding of the movement rates of the overall area is crucial.

The southern part of Anchor Bay is instead characterised by vertical Upper Coralline Limestone cliffs which directly reach the sea. The absence of outcrops of the Blue Clay Formation prevents the occurrence of lateral spreading phenomena on this side of the bay.

The climate is typically Mediterranean, with hot, dry and long summers, warm and short winters. In the last 50 years the average annual precipitation is of about 550 mm, hardly exceeding 800 mm, with an average of about 70 rainy days per year.

Methods and Results

The investigations have been developed through a multidisciplinary approach which has envisaged the following methods and techniques:
– GPS monitoring
– Tape extensometer measurements
– SAR interferometric analyses
– GPR survey.

GPS Monitoring

GPS techniques have been already proved to be a powerful tool in ground deformation analysis. Several papers dealing with landslide monitoring demonstrated the capability of GPS to measure deformations with high accuracy and reliability (Gili et al. 2000; Malet et al. 2002; Coe et al. 2003; Lissak et al. 2010). For this reason, a GPS monitoring network has been installed since October 2006 and is still operating. The first aim of the installation of the network was to define whether rock spreading and block sliding phenomena were active at Il-Prajjet and, if so, to determine the rates of movement within the unstable area.

GPS measurements have been taking place with reference to eight benchmarks spread all over the unstable area. Within the upper sector, corresponding to the edge limestone plateau, three benchmarks were installed, whereas five more benchmarks were positioned on the large blocks overhanging the buildings of the tourist infrastructure (Fig. 6). In order to guarantee the uniformity of the surveys, avoiding positioning errors, a forced centring device for the antenna was performed for each benchmark.

Considering the extremely slow rate of deformation, GPS surveys have been conducted using at least two dual frequencies receivers, using a static relative positioning technique, which achieve more accurate results. It was chosen a period of acquisition of 20 min and a 2 s sampling rate. Field monitoring activities have been planned using broadcasting almanacs to exploit the temporal windows with the best possible satellite configuration within a reliable value of the GDOP parameter.

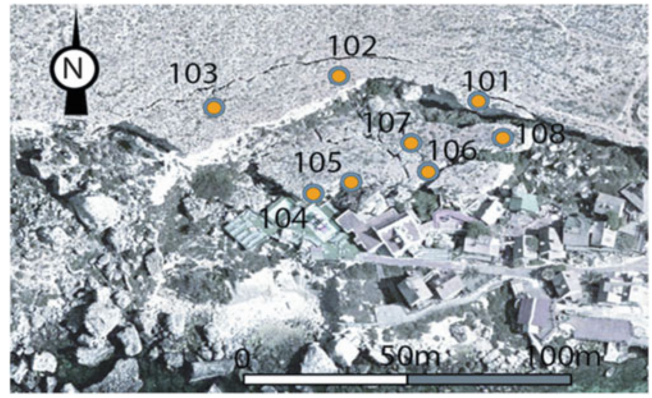

Fig. 6 The aerial photograph shows the benchmarks installed in the areas affected by rock spreading (101–103) and block sliding (104–108)

Table 1 Cumulative planar and vertical displacements measured by means of the GPS technique at Il-Prajjet during the period October 2006–November 2010

Benchmark	Planar displacement (cm)	Vertical displacement (cm)
101	2.9	Negligible
102	2.7	5.8
103	3.2	10.2
104	5.8	4.0
105	5.2	4.0
106	3.4	Negligible
107	5.0	Negligible
108	2.8	Negligible

Surveys have been carried out twice per year, in March and November, corresponding to the end of the wet season and the end of the dry one, respectively, in order to investigate the relationship between landslide activity and rainfall.

Since the first GPS measurements it was clear that both the rock spreading and block sliding sectors were active, affecting a large area of Il-Prajjet. The series of readings carried out over a 49 months period (October 2006–November 2010) showed significant displacements of all the eight benchmarks, with cumulative displacements ranging from 2.7 to 10.2 cm. In particular, vertical displacements appeared to be higher in the area affected by rock spreading (benchmark 103 was lowered of 10.2 cm and benchmark 102 of 5.8 cm) while planar movements prevail in the block sliding sector (benchmark 104 was lowered of 5.8 cm and benchmark 105 of 5.2 cm) (Fig. 6, Table 1).

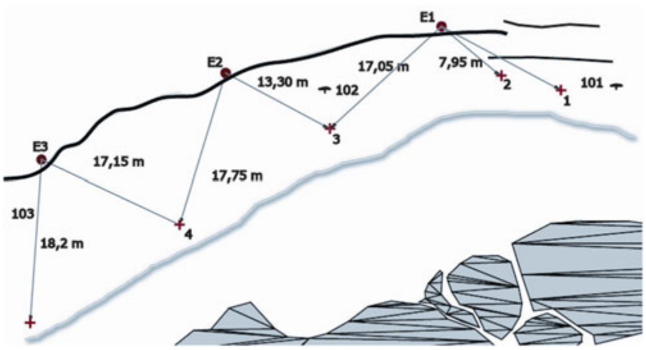

Fig. 7 Tape extensometers measure the relative distances between couple of reference points, located on the rock spreading scarp and on the rock mass beneath

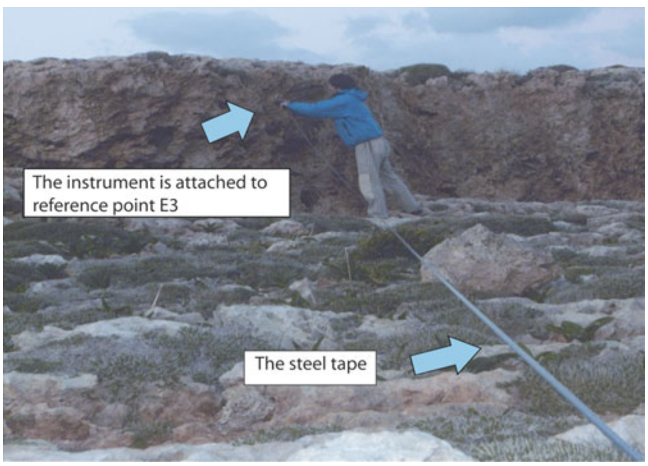

Fig. 8 The extensometer is anchored by the operator to a reference ring on the main scarp and to another ring located on the rock mass beneath

Tape Extensometer Measurements

A tape extensometer network has been installed in the area affected by rock spreading at the end of December 2009. Tape extensometer is a mobile instrument, equipped with a micrometer which can measure distances reaching 20 m, with a sub-millimetre precision. An invar steel tape has been used to monitor relative changes in the distance between couple of reference points (Figs. 7 and 8).

Reference points have been placed in the area where rock spreading is more active. In particular, reference points E1, E2 and E3 have been anchored to the main scarp within the rock spreading sector (Fig. 8). The surveys have been carried out approximately every 3 months, corresponding to the end of each season.

Table 2 shows relative ground deformations recorded along seven scanlines, connecting couples of reference points, during three field surveys performed in 2010. The two higher cumulative displacements have been measured between the couples E2-4 and E3-5 (Fig. 8), reaching a total annual rate of deformation respectively of 5.6 and 4.0 mm. The displacements recorded in the eastern sector are lower and do not exceed 3.0 mm, confirming that the western sector is the most active area affected by rock spreading phenomena.

Table 2 Deformations recorded during 2010

Scanline	Displacement March (mm)	Displacement July (mm)	Displacement November (mm)
E1-1	+3.2	−6.5	+3.45
E1-2	+3.9	−4.1	+3.25
E1-3	+12.9	−7.5	−2.80
E2-3	+0.1	−2.45	−0,25
E2-4	+0.90	−1.60	+6.30
E3-4	+2.05	−4.35	+0.80
E3-5	+0.20	−1.90	+5.70

Positive rates correspond to cumulative widening of fractures (sliding movement towards the plateau), whereas negative values display narrowing of fractures

Tape extensometer results have been correlated with GPS displacements, recorded by benchmarks 101, 102, and 103 (cf. Fig. 6), Finally, the outputs of these techniques showed comparable movement rates.

Interferometric Analyses

To support the monitoring results, interferometric analyses (satellite SAR) have been carried out along all the north-western coast of the Island of Malta. The analyses of radar images consisted in two phases. In a first phase, the database of ERS 1 and ERS 2 images, collected since 1992, has been exploited to evaluate the deformation eventually occurred before the realization of the GPS network. In a second phase, images acquired from ENVISAT satellites have been processed in order to define the state of deformation in the last decade.

In particular, the interferometric analysis of the latter satellite images were aiming at the integration and validation of the results achieved with the GPS technique. To detect and monitor ground movements classical DInSAR (advanced Differential Sar Interferometry) and PSI (Persistent Scatterers Interferometry) have been applied, which can reach a subcentimetric precision. Table 3 shows the number of images processed and the time period covered by satellites data.

PSI conducted over the entire stretch of the north-western coast highlighted the presence of deformation induced by lateral spreading phenomena. Tens of limestone boulders with a scatterer point-wise behaviour recorded rates of displacement along the sensor line of sight (23 ° with respect to the vertical) ranging from 1.5 to 4 mm/year. Unfortunately,

Table 3 Satellite images used for interferometric analyses

Platform	Images	First image	Last image
ERS 1	14	05/06/1992	14/01/1996
ERS 2	41	15/01/1995	04/12/2000
ENVISAT	33	28/04/2003	20/07/2009

Fig. 9 GPR data acquisition (profile spacing 1 m; trace interval 5 cm)

no natural persistent scatterers were so far detected over the site of Il-Prajjet where the GPS network has been installed and therefore a validation of the results is at present unfeasible.

GPR Survey

Geophysical surveys have been carried out to investigate the geometry of the limestone blocks which are located beneath the rock spreading area and to identify the underground contact with the Blue Clays. Data were acquired using a Ground Penetrating Radar (GPR) equipped with 300 and 500 MHz bistatic shielded antennas. Profiles were recorded along a dense grid (22 m by 7 m wide) (Fig. 9). 2D processed GPR data were combined in order to obtain a 3D data volume. The GPR technique allowed us to recognise (1) a high-reflective zone interpreted as layered limestones; (2) a semi-transparent portion interpreted as non-stratified, massive limestone (probably the Mtarfa Member of the Upper Coralline Formation) and (3) a high-attenuating area having its top at a depth of about 13 m. The latter level corresponds to the contact between the limestone blocks and the Blue Clay Formation. In addition, several evident vertical or sub-vertical discontinuities have been outlined, showing high persistencies (Fig. 10).

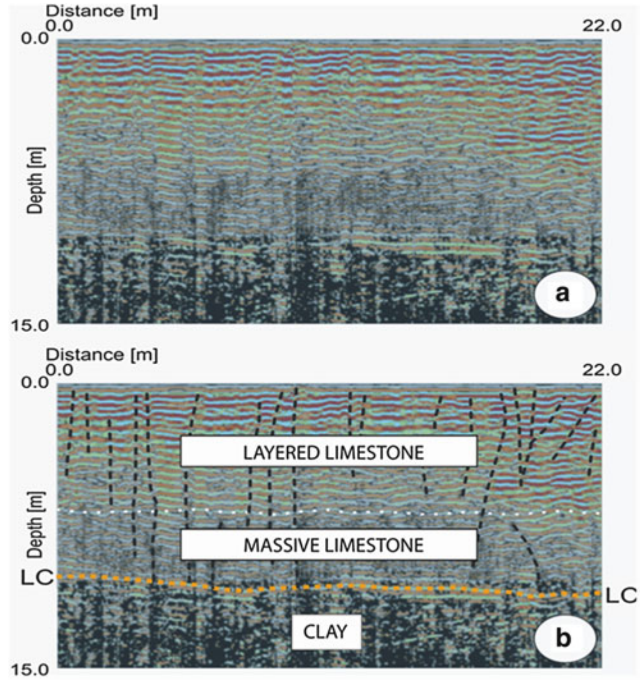

Fig. 10 Example of processed and depth-converted 300 MHz GPR profile (cosine of instantaneous phase superimposed on reflection amplitude) acquired on the widest limestone block within the block slide area (**a**) and the same profile with interpretation superimposed (**b**). LC corresponds to the contact between the limestone blocks and the Blue Clay Formation. Several vertical or sub-vertical discontinuities are outlined. The deepest portion of the limestone blocks shows low amplitude reflections and can be interpreted as a massive material, while the shallowest part is clearly layered. The profile is plotted without vertical exaggeration

Conclusions

A spectacular case of rock spreading evolving into block sliding has been investigated at Il-Prajjet, a small inlet located along the north-western coast of the Island of Malta. Slope instability processes in the area are strictly linked to the geological and structural settings of the bay, which foresees the superimposition of deeply jointed limestones on clayey materials.

The multidisciplinary and integrated approach applied within the study has allowed the understanding of the present evolution of the instability phenomena affecting Il-Prajjet and has provided the basis for defining future scenarios of evolution, which are essential for the assessment of hazard to which the tourist attraction located in the area is exposed.

In particular, the integration of results obtained from different monitoring systems, such as GPS and tape extensometer, has proved to be fundamental to define the state of activity and the rate of movement of both rock spread and block slide. In addition, the outputs of GPR surveys have provided detailed information on the geometry and volumes involved in the block slide as well as the location of the limestone-clay contact and discontinuity persistence values, which are essential to implement a proper subsurface geological model of the unstable area. Finally, the preliminary results of interferometric analyses, which actually refer to the entire north-western coast of Malta, show ongoing deformation which has however to be further analysed with respect to the study area of Il-Prajjet.

Acknowledgments The research activities were funded by (i) the EUR-OPA Major Hazards Agreement of the Council of Europe through the European Centre of Geomorphological Hazards (CERG) in the frame of the project "*Coastline at risk: methods for multi-hazard assessment*" (Co-ordinator M. Soldati) and (ii) the Fondazione Cassa di Risparmio di Modena and Reggio Emilia within the project *Multidisciplinary research in the open-air laboratory of the island of Malta: an international network for landslide hazard assessment in coastal areas* (Co-ordinator M. Soldati).

Interferometric analyses have been carried out under an ESA Category-1 project (C1P.7044). The authors acknowledge the European Space Agency for providing ERS and ENVISAT data.

The authors are also thankful to Darren Saliba for his precious collaboration during field work and Julie Anne Mizzi for her helpful suggestions about Maltese geology.

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