Landslides Along the North-West Coast of the Island of Malta

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Abstract

The paper shows the results of geomorphological and engineering-geological investigations carried out along the north-western coast of the Island of Malta, with special emphasis on landslides. Field surveys and aerial-photo interpretation allowed the recognition, identification and mapping of a series of landslides of different type and size, some of which showing evidence of activity. Coastal instability in the studied area is deeply controlled by structural factors, such as tectonic and stratigraphic ones. The research envisaged a multidisciplinary approach, which also included landslide monitoring in specific sites which were selected for detailed investigations, owing to the peculiarity of the instability processes occurring and for the related hazard and risk conditions. The paper outlines the research phases and the results achieved which proved to be fruitful thanks to the application of different methodologies for the study of coastal landslides. Particular attention has been paid to rock spreading phenomena, which are widespread along the north-western coast of Malta due to the superimposition of limestones over clayey terrains.

Keywords

Coastal geomorphology • Landslides • Rock spreading • Malta

Introduction

This paper presents the outputs of field surveys and aerial-photo interpretation carried out along the north-western coast of the Island of Malta, which is located in the central Mediterranean Sea between Africa and Sicily. The investigations were focused on landslides along a coastal stretch of 15 km^2 comprised between Marfa Ridge to the north and Il-Pelegrin promontory to the south (Fig. 1).

Previous literature describes in detail the geological features and evolution of the Island of Malta (cf. Pedley et al. 1978; Illies 1981; Pedley et al. 2002), whereas geomorphological features have only rarely been investigated (Alexander 1988). However, a series of papers has recently highlighted the most interesting geomorphological features of the north-western coast of the Island of Malta, with particular reference to mass movements (Dykes 2002; Farrugia 2008; Magri et al. 2007, 2008; Magri 2009; Soldati et al. 2010; Coratza et al. 2011).

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C. Margottini et al. (eds.), *Landslide Science and Practice*, Vol. 1,
DOI 10.1007/978-3-642-31325-7_7,

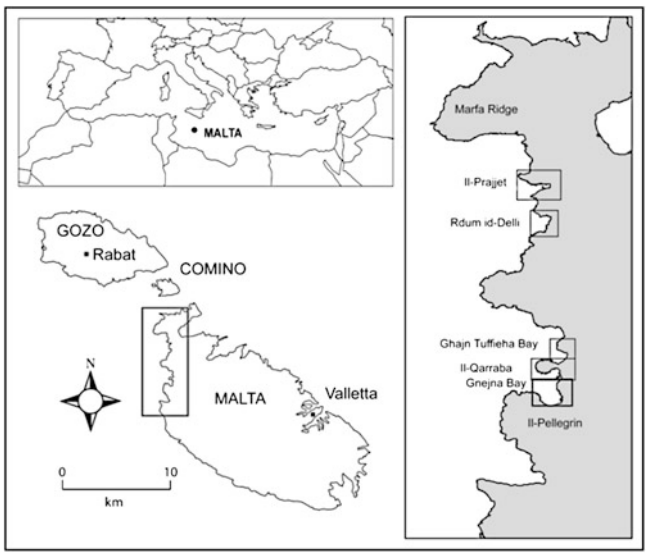

Fig. 1 Location of the study area

The research has included the recognition, identification, mapping and monitoring of different types of landslides occurring in the study area. Among these, worthy of note are extensive lateral spreading phenomena which are favoured by the different mechanical properties of the two main rock types outcropping in the area, such as those belonging to the Upper Coralline Limestone and the Blue Clay formations (cf. Oil Exploration Directorate 1993).

The research has been carried out in the frame of a project entitled "*Coastline at risk: methods for multi-hazard assessment*", funded by the EUR-OPA Major Hazards Agreement of the Council of Europe during the period 2009–2011. The project is managed by the European Centre on Geomorphological Hazards (CERG) and deals with the study of slope instability in critical coastal areas of Malta, France (Normandy) and Central Portugal. The study has been co-funded by 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-ordinated by the University of Modena and Reggio Emilia and supported by the Fondazione Cassa di Risparmio di Modena. The aims of the above mentioned projects have been pursued through multidisciplinary investigations integrating geomorphological and engineering-geological approaches. Avant-garde research techniques, both traditional and innovative, have been applied with special reference to mapping and monitoring of coastal instability phenomena. The results achieved make up a significant step toward the final objective of the CERG project which is to propose a method for coastal multi-hazard assessment that can be used to face and manage coastline hazards in Europe.

The Study Area

The study area is located in the Island of Malta, in particular on its north-west coast.

The Maltese archipelago lies approximately 96 km south of Sicily and 290 km north of Africa. From north to south, Malta consists of three main islands: Gozo, Comino and Malta, the latter being the largest, with an area of 246 km^2 (Fig. 1).

From a geodynamical point of view, the Maltese Islands lie in the Sicily Channel, which has been affected during Neogene-Quaternary (Finetti 1984) by continental rifting which produced extensive structures, such as the Pantelleria, Malta and Linosa tectonic depressions controlled by the NW-SE-trending Pantelleria Rift (Argnani 1990; Civile et al. 2010). The Maltese tectonic setting is characterised by two intersecting fault trends: the NW-SE-trending Pantelleria Rift and the ENE-WSW graben system, dominated by the Victoria Lines fault, which makes up the main tectonic discontinuity of Malta. From a structural viewpoint, the Island of Malta is actually divided into two regions by the Victoria Lines fault. A series of pronounced horst and graben features, oriented ENE-WSW, occurs north of the fault and deeply influences the morphology of the northern stretch of the island, which is thus characterised by prominent ridges and well-shaped-valleys.

The Maltese archipelago is characterised by a warm climate with prolonged summers and mild winters. As in typical Mediterranean climate conditions, precipitation is concentrated in the cold season. The mean annual value of precipitation in the Island of Malta is of 550 mm (period 1922–2007). The relatively flat topography does not influence the distribution of rainfall on the island.

Geological and Geomorphological Settings

The Maltese archipelago is composed of Tertiary limestones, clays and marls capped by thin superficial deposits, such as red soils or alluvial/colluvial sediments.

The bedrock consists of sedimentary rocks, deposited in a period of time comprised between Miocene and Upper Oligocene, that is from about 30 million to about 5 million years ago (Pedley et al. 1978, 2002).

The *Lower Coralline Limestone Formation* (Upper Oligocene) is the oldest unit of the stratigraphic sequence. It is characterised by hard, pale grey limestones made by

reef-building organisms and reef-related sediments. It outcrops mainly in Gozo and southern Malta where it is responsible for forming spectacular cliffs, some reaching 140 m in height.

The *Globigerina Limestone Formation* (Lower-Middle Miocene) lies above the Lower Coralline Limestone Formation and widely outcrops at the sea level in the study area. The Formation is made up of fine-grained and lightly-cemented limestones, which vary in thickness from 20 to over 200 m. The fair qualities of the Globigerina limestone and the exposition to wave action are the causes of extensive rock falling.

The stratigraphic sequence continues with the *Blue Clay Formation* (Middle Miocene) which can reach a thickness of 65 m and is composed by silty sand, marls or clays. The poor geotechnical quality of sediments has favoured the shaping of gentle slopes which are sometimes used by locals for agricultural purposes, such as at the Marfa Ridge or along the slopes of Gnejna Bay.

The stratigraphic sequence ends up with the *Upper Coralline Limestone Formation* (Upper Miocene) which is mainly composed by shallow marine sediments, the youngest outcropping in the Maltese archipelago. The Formation is affected by a dense network of tectonic discontinuities which provide the rock masses with a brittle behaviour. The limestones often show karst features such as sinkholes and caves. Karst is also the cause of barren grey pavements inland. The presence of the Upper Coralline Limestone Formation gives rise to vertical cliffs of varying heights along the coastline, which range from a few metres to over 30 m.

The different mechanical behaviour of the Blue Clay and the Upper Coralline Limestone formations favours the development of a series of landslides of different type and size which widely affect the north-western coastline of Malta (Fig. 2). Landslides are locally favoured by coastal erosion, which induces hazardous situations that urge to be investigated in order to prevent risk for population, buildings and infrastructures. However, it should be emphasised that locally rock blocks deposited at the sea level protect the shoreline from marine erosion.

Rock spreading phenomena are clearly favoured by the above mentioned stratigraphic setting. Evidence of rock spreading is widespread all along the edges of the Upper Coralline Limestone plateaus. Outstanding examples have been recognised at Il-Qarraba (Ghajn Tuffieha Bay) (Fig. 3), Il-Prajjet (Anchor Bay) and along the western sector of Marfa Ridge. The lateral extension of rock masses tend to evolve into *block sliding* whose onset is extensively witnessed by scattered blocks of variable size lying on the clayey slopes which gently degrade toward the sea.

Rock falls and *topples* are abundant along the coastline and mainly affect the Upper Coralline Limestones Formation which is characterised by persistent fissures and cracks of tectonic origin, locally widened by lateral spreading

Fig. 2 The superimposition of the Upper Coralline Limestone Formation on the Blue Clay Formation is a predisposing cause of landslide occurrence along the north-west coast of Malta (Courtesy of Ten. Col. M. Marchetti)

(Fig. 4). The Lower Coralline Limestone and the Globigerina Limestone formations are also affected by these types of movement.

Earth flows and *earth slides* occur along clayey slopes and are triggered by rainfall during the autumn and winter months, when the clay material becomes wet, also due to the infiltration of water coming from the overlying limestones (Mangion 1991). After dry summer periods, deep desiccation cracks develop in the Blue Clay terrains which are able to convey a significant amount of water inside the slopes during the following wet season, increasing pore pressure and favouring the occurrence of mass movements (Dykes 2002; Magri et al. 2008). The latter occur especially where the vegetation cover is scarce or missing, such as at Rdum-id-Delli and Ghajn Tuffieha Bay.

Methods and Results

The investigations on landslides along the north-western coast of the Island of Malta have been developed through a multidisciplinary approach which envisaged the following research phases:

Fig. 3 Il-Qarraba promontory at Ghajn Tuffieha Bay. The superimposition of limestones on clayey terrains favours the onset of rock spreading phenomena and of associated landslides which occur at the edges of the plateaux

Fig. 4 Evidence of rock falls occurring along the north-western coast of Malta (Courtesy of Ten. Col. M. Marchetti)

- Retrospective analysis of landslide occurrence;
- Analysis of climatic data;
- Interpretation of multi-temporal aerial photographs;
- Geomorphological survey and mapping;
- Landslide monitoring.

The study area can actually be considered as a natural laboratory for the study of landslide phenomena and their geomorphological hazard and risk implications and for the peculiar geological and geomorphological conditions.

As a consequence, the application of integrated research methods and techniques, with special reference to mapping and monitoring of coastal instability, proved to be particularly fruitful in terms of testing methodologies and achievement of significant results.

Retrospective Study on Landslide Occurrence

The first phase of the research has consisted of a retrospective study on landslide events that took place within the research area during historic times. Bibliographic and archival research has been carried out at public and private institutions and on newspapers. The aim was to obtain a comprehensive picture on slope instability and define the spatio-temporal distribution of past landslide events, whilst at the same time identifying useful elements for typological definitions. However, the information available has given quite a scattered picture of the temporal occurrence of landslides in the study area (Magri 2009). Information was available only for those cases in which significant damage was caused.

Analysis of Climatic Data

Climatic data have been obtained from the Luqa meteorological station (located at the centre of the Island of Malta), monitored since 1920, to determine the relationship between the identified landslide events and particular meteorological conditions. Data regarding the total annual amounts of rainfall for the period 1929–2007, the average monthly precipitation for the period 1922–2007 and the maximum monthly precipitation for the period 1922–2007 have been collected and analysed.

In particular, the annual average precipitation during the above mentioned period is of 550 mm. However, it should be noticed that annual average precipitation has varied significantly throughout that period, ranging from about 400 to 1,000 mm per year. During the last decade, notable variations have also been recorded, being the year 2003 the rainiest with an average of 837 mm and 2004 the driest with 455 mm. These rainfall variations have to be properly taken into account to define the role of precipitation on landslide occurrence.

Interpretation of Multi-temporal Aerial Photographs

A multi-temporal analysis of aerial photographs has been completed with special attention given to landslide phenomena. To achieve this aim both traditional stereoscopic techniques and digital photogrammetry techniques have

been used. The study of landforms represented in a sequence of images corresponding to different years enabled to reconstruct the evolution of the coastal stretch under study. Aerial photographs available for the north-western coast of the Island of Malta have been selected and analysed. Particular attention has been given to the first and last series of aerial photographs available (1957 and 2008).

Geomorphological Survey and Mapping

A geomorphological survey has been carried out at a scale of 1:5,000 for the entire north-western coastal stretch of the Island of Malta. This phase of the research has also included a check and update of the existing geological map (Oil Exploration Directorate 1993) as well as investigations aiming at the recognition of ductile and fragile deformation features, which are of topical importance for the assessment of slope stability. This phase has finally led to the production of a detailed geomorphological map that covers the coast between Marfa Ridge to the north and Victoria Lines fault to the south. Mapping has been conducted following the guidelines of the Italian Geological Survey (Gruppo di Lavoro per la Cartografia Geomorfologica 1994), which foresee the representation of landforms according to their genesis with indication of their state of activity by means of colours, symbols and retina.

Particular attention has been paid to the mapping of landslides which make up a predominant feature along the investigated coastline. Landslides have been distinguished according to the following types of movement and their areal distribution was calculated: (1) rock falls, including topples (18%); (2) earth flows and earth slides (3%); (3) rock spreads (14 %) and (4) block slides (65 %) (Fig. 5).

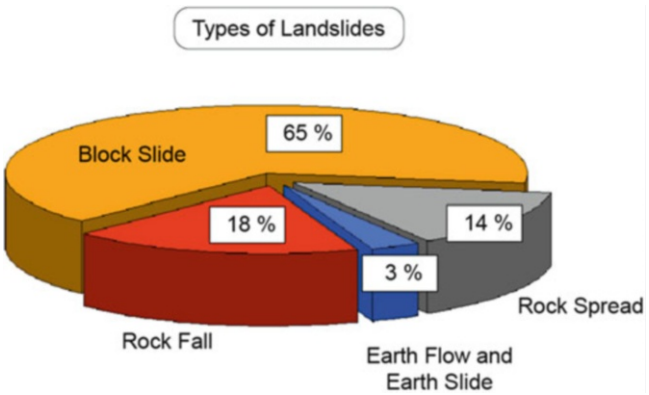

Fig. 5 Areal distribution of landslide types along the north-west coast of Malta with respect to the total area affected by landslides

Fig. 6 Evidence of large block sliding occurring at Il-Prajjet (Anchor Bay) as a consequence of rock spreading phenomena affecting the Upper Coralline Limestone Formation

Landslide Monitoring

In-depth investigations have been focused on two sites where exemplary cases of rock spreading and associated movements, which induce hazard and risk situations, were identified. This is the case of Il-Qarraba at Ghajn Tuffieha Bay (Fig. 3) and Il-Prajjet at Anchor Bay (Fig. 6). These sites have been monitored to determine whether rock spreading phenomena, and associated block slides, were active and, in case, which was the rate of movement. This was considered as crucial for hazard assessment at the two sites.

Actually, landslide monitoring had already started in 2005 at these two sites, with the onset of two GPS monitoring networks on rock plateaus. The networks consist of 2 reference stations and 17 benchmarks spread all over the unstable areas. The first measures already showed that the identified and monitored rock spreading phenomena were active (Magri et al. 2007, 2008) and worth of being monitored for longer periods, in order to define their rate of movement and possible relationships with precipitation patterns.

Therefore field-monitoring campaigns have been continued, and further instrumentation used, in the frame of the research project here described. This has happened approximately every 6 months, in April and October/November, corresponding to the end of the wet and dry seasons. These periods have been chosen in order to define the role of rainfall in the deformation processes.

The results of the GPS technique on the investigated rock spreading phenomena have shown vertical displacements that exceed 10 cm in the last 4 years and horizontal ones almost reaching 3 cm, namely at Il-Prajjet (Anchor Bay). In order to continuously monitor the displacements along the more active fractures, extensometers were installed in 2010 along some cracks at Il-Prajjet (Anchor Bay).

Fig. 7 Hazardous situation south of Il-Qarraba promontory due to the presence of limestone blocks in critical stability conditions. It should be noted that the blocks are overhanging footpaths and beach areas

The trend of movement seems to be sensitive to seasonality, in relation to rainfall distribution, but further data are needed to properly define this issue.

Discussion and Conclusions

The north-western coast of the Island of Malta displays a wide variety of landslides of different type, size, state and rate of activity. Coastal instability processes are strictly linked to the structural setting of the area which is characterised by the superimposition of deeply-jointed limestones on clayey materials.

The integration of geomorphological survey, aerial-photo interpretation and landslide monitoring enabled the definition of the state of activity and rate of movement of the rock spreading phenomena which affect two specific sites within the study area. This is of fundamental importance as far as landslide hazard is concerned, since lateral spreading phenomena may favour the occurrence of collateral movements (cf. Pasuto and Soldati 1996), such as block slides, rock falls and topples as well as earth slides and flows, which may induce sudden risk situations (Fig. 7).

The results of this research are aiming at providing local authorities with a sound knowledge of the causes of coastal instability phenomena and means to face related risks. Actually, the north-western coast of Malta is one most aesthetically pleasant areas in the island and therefore it attracts tourists and locals in all seasons. Moreover, since this area perfectly integrates natural and cultural heritage (Coratza et al. 2011), it is likely that the number of visitors will increase in the near future, since these aspects are likely to be further exploited and promoted within the sphere of tourism, where a different niche can be created. Therefore, the need to provide safe conditions for visitors – preserving at the same time this valuable strecht of coast – is clear (May 2008; Panizza and Piacente 2008; Soldati et al. 2008a).

The research team has tried to identify strategies to involve and sensitize technical and administrative staff from public institutions responsible for the protection of the environment, as well as academic staff, towards aspects of landslide hazard and risk assessment and mitigation. This has also included scientific workshops and meetings (Soldati et al. 2008b) and the use of the study area as a teaching/demonstration medium for Maltese and foreign stakeholders, as well as students and young researchers (Soldati et al. 2010).

Acknowledgments The research activities were funded by (1) the EUR-OPA Major Hazards Agreement of the Council of Europe through the European Centre on Geomorphological Hazards (CERG) in the frame of the project "*Coastline at risk: methods for multi-hazard assessment*" (Co-ordinator M. Soldati) and (2) the Fondazione Cassa di Risparmio di Modena 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).

The Authors are grateful to Dr. Simon Mercieca, Director of the Mediterranean Institute of the University of Malta, for the continuous support offered.

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