An investigation of mass movement processes along the northern coast of Malta

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Summary. In Malta there are very clear associations between tectonics, structural geology and geomorphology. This relationship is especially evident at the coastal zone in the northern region, which despite its small size shows a great variety of features and processes. The northern region has been influenced by a rift system striking 50° to 70°. To the south, the northern region is bounded by the Great Fault. This paper reports the results of a geomorphological survey undertaken north of the Great Fault which is the most significant topographic feature of the Island. North of this fault, the geological structure is dominated by the development of horst and graben blocks, indicated by prominent ridges and valleys, and bounded by ENE trending normal faults. The relationship between geology and geomorphology and the spatial distribution of coastal landforms, especially landslides, occurring in this Region have been identified through a geomorphological survey. Moreover at three field sites, slope instability has been investigated in more detail through geomorphological mapping, geotechnical testing of the material and slope stability analysis. From physical and geotechnical laboratory data it has been concluded that Rdum id-Delli is the most stable site, Gnejna Bay shows stability with a trend towards instability whereas Ghajn Tuffieha Bay is the site most prone to instability.

Keywords: geomorphological survey, geotechnical testing, slope stability analysis, mass movement, Malta.

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Introduction

Mass movement is the downslope movement of soil or rock material under the influence of gravity without the assistance of moving water, ice or air (Selby, 1993). The distinction between mass movement and the transport of material by other denudational processes is not always clear in practice for example with regards to fluvial transport and glacier flow. Mass wasting is often regarded as synonymous with mass movement. However the former term is also used in a wider context to include all processes involved in the lowering of the landscape (Summerfield, 1991).

Over the years, several classifications have been proposed to try to classify mass movement processes and landforms (for example Sharpe, 1938; Varnes, 1958, 1978; Carson and Kirkby, 1972; Hutchinson, 1988) on the basis of different criteria such as velocity and mechanism of movement, type of material, water content available in the material, physical properties, slope and landslide geometry, shape of failure surface and post-failure debris distribution. Given the great diversity in terms of form, origin, movement and magnitude, no single classification is universally satisfactory. The most generally accepted classification is the complex approach proposed by Varnes (1978) (Figure 1) where the main categories are linked to the processes of fall, slide, flow and creep (Goudie et al., 1994). However more recent classifications do exist, the most common being those proposed by Cruden and Varnes (1996) and Dikau et al. (1996).

There is little knowledge on mass movement processes and slope instability in Malta due to limited geomorphological studies. The work carried out by Dykes (2002) dealing with mass movement processes on the north-west coast and taking also into consideration issues on conservation management in Malta, is a notable exception. This paper presents research on mass movement processes along the northern coast in Malta. The northern region on mainland Malta is bounded by the Great Fault, also known as the Victoria Lines Fault, which crosses Malta from west to east and forms a fault scarp which is the most significant topographic feature of the Island. The principal aim of this study is to investigate the types of mass movement processes occurring in this Region, focussing on coastal slope instability in the Blue Clay formation. This paper first considers the regional setting of the Maltese Islands providing also information on characteristic climate and vegetation. The relationships between the geological formations and associated landforms together with the role of tectonics on the structural geology, especially with regards to the northern region are then discussed. The second part of the paper reviews in detail mass movement processes present along the northern coast and examines slope instability in the Blue Clay Formation. A detailed geomorphological survey has been undertaken to provide information for the above objectives together with geotechnical testing of...
Figure 1: Varnes (1978) classification of landslides (Cooke and Doornkamp, 1990).
the Blue Clay material and slope stability analysis. A number of published and unpublished sources were consulted together with observations from coastal aerial photographs and topographic maps.

**Regional setting of the Maltese Islands**

**Location**
This study was conducted in Malta, the main island of the Maltese archipelago located in the central Mediterranean region between Italy and North Africa, at a latitude of 35°48′28″ to 36°05′00″ North and a longitude of 14°11′04″ to 14°34′37″ East (Figure 2). The archipelago consists of two other islands, Gozo and Comino and a number of small uninhabited islets, the two main ones being Cominotto (Maltese: Kemmunett) and Filfola (better known by its Maltese name Filfla). The Islands have a total land area of 316 km² and a coastline about 190 kilometres long, with a submerged area (up to 100 metres) of 1,940 km² (Schembri, 1990). The length of the whole archipelago is 45 kilometres.

**Climate and vegetation**
The climate of the Islands is typically Mediterranean with mild, wet winters and hot, dry summers. The average annual precipitation is 530 mm (mean for the period 1951-1990) but evapotranspiration reaches 942 mm. Rainfall is highly variable from year to year; some years are extremely wet whereas others are very dry. The rainfall period usually occurs from October to March, the dry period usually extends from April to September (Chetcuti et al., 1992). Temperatures rarely fall below 5°C but can rise up to 35°C and more in the very hot summer months. The Islands are very windy with only 7.7 per cent of the days of an average year being calm. This study was conducted in Malta, the main island of the Maltese archipelago located in the central Mediterranean region between Italy and North Africa, at a latitude of 35°48′28″ to 36°05′00″ North and a longitude of 14°11′04″ to 14°34′37″ East (Figure 2). The archipelago consists of two other islands, Gozo and Comino and a number of small uninhabited islets, the two main ones being Cominotto (Maltese: Kemmunett) and Filfola (better known by its Maltese name Filfla). The Islands have a total land area of 316 km² and a coastline about 190 kilometres long, with a submerged area (up to 100 metres) of 1,940 km² (Schembri, 1990). The length of the whole archipelago is 45 kilometres.

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The vegetation of the Maltese Islands corresponds to the Mediterranean biome, since the Islands have a similar type of climate and lie within the Mediterranean region. A semi-arid environment characterises the Maltese archipelago and the vegetation can be divided into woods, maquis, garigue and steppe (Lanfranco, 1992). Evergreen woods have been virtually destroyed, although several replantings have taken place. The maquis vegetation, which is of secondary origin, is still widespread especially on the sides and bottoms of the dry valleys (Maltese: widien). Garrigue is the most typical of the Maltese vegetation communities and is characteristic of the karstic rocky regions of the Islands, although this is declining rapidly due to urban sprawl and other forms of disturbance. Steppic vegetation is very widespread with a great diversity of species. A particularly interesting steppic community occurs on clay slopes. Due to the high level of human impact, disturbed ground has become the most widespread habitat over the Islands. Many of the species found are aliens or adventives which have become naturalised over the years (Lanfranco, 1992).

**Geological formations and geomorphological features**
The Maltese Islands are entirely composed of Tertiary limestones with subsidiary marls and clays. Quaternary deposits, mostly Pleistocene in age, are limited to few localities. These deposits have been studied in detail by Trechmann (1938) who has classified them into valley loams and breccias, coastal conglomerates and breccias, and ossiferous deposits in caves and fissures. This succession represents a varied cross-section of Oligo-Miocene lithologies and facies, but consists almost entirely of carbonates deposited within a variety of shallow water marine environments (Pedley et al., 1978).

In many respects these resemble the mid-Tertiary limestones occurring in the Ragusa region of Sicily and North Africa. The succession gives the impression that the depositional area first subsided and then there was a gradual shallowing (Felix, 1973). Deposition occurred in the following simple succession. Lower Coralline Limestone is the oldest formation and first deposited. This was followed by Globigerina Limestone, Blue Clay, Greensand and Upper Coralline Limestone which is the youngest formation and last deposited. Table 1 presents in detail the litho- and chronostratigraphy of the Maltese Islands whereas Figure 3 shows a geological map of the Maltese Islands.

<table>
<thead>
<tr>
<th>Epoch</th>
<th>Stage Age in Ma</th>
<th>Formation</th>
<th>Max. thickness (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper Miocene</td>
<td>Tortonian</td>
<td>Upper Coralline Lst.</td>
<td>104-175</td>
</tr>
<tr>
<td></td>
<td>(12-7.5)</td>
<td>Greensand</td>
<td>0-16</td>
</tr>
<tr>
<td>Middle Miocene</td>
<td>Serravallian</td>
<td>Blue Clay</td>
<td>0-75</td>
</tr>
<tr>
<td></td>
<td>(13-12)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lower Miocene</td>
<td>Burdigalian</td>
<td>Middle Globigerina Lst.</td>
<td>5-20</td>
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<tr>
<td></td>
<td>(20-15)</td>
<td>Lower Main Conglomerate</td>
<td></td>
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<td>5-110</td>
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<tr>
<td></td>
<td></td>
<td>C1</td>
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<tr>
<td>Upper Oligocene</td>
<td>Chattian</td>
<td>Lower Coralline Lst.</td>
<td>140</td>
</tr>
</tbody>
</table>

Table 1: Stratigraphy of the Maltese Islands (Pedley et al., 1978; Alexander, 1988). Lithostratigraphy mainly after Murray (1890); chronostratigraphy after Felix (1973).

The geological formations of the Islands are very distinctive lithologically and this is reflected in characteristic topography and vegetation (House et al., 1961). The Lower Coralline Limestone is responsible for forming spectacular cliffs, some reaching 140 m in height, which bound the Islands especially in the west. Inland, the Lower Coralline Limestone forms barren grey limestone-pavement topography. The succeeding Globigerina Limestone, which is the most extensive formation on the Islands, forms a broad, rolling landscape. The soil is thin but intensively cultivated and
Figure 2: Location of the Maltese Islands in the Central Mediterranean Region (adapted from Alexander, 1988).

Figure 3: Geological map of the Maltese Islands (Adapted from Geological Map of the Maltese Islands, 1993, Oil Exploration Directorate, Office of the Prime Minister, Malta, scale 1: 25000).
hillslopes are densely terraced. The Blue Clay produces slopes that tend to slide over the underlying Globigerina Limestone Formation. It forms the most fertile bedrock on the Islands, especially where springs seep from the overlying Upper Coralline Limestone. The latter, which also includes Greensand, forms massive cliffs and limestone pavements with karstic topography similar to Lower Coralline Limestone.

Structural geology and tectonics
The predominant control on landforms in Malta is undoubtedly that of tectonic activity including faulting, uparching and subsidence. Stream channel formation and incision, coastal morphology, erosion surface formation and scarp morphology have all responded sensitively to the tectonic events of the last 15 Ma (Alexander, 1988). Tectonics have also played an important role on the geological structure of the Maltese Islands.

The geological structure is usually divided into three main regions: Malta north of the Great Fault, Malta south of the Great Fault and Gozo (House et al., 1961; Pedley et al., 1976, 1978). For the purpose of this study, the region north of the Great Fault is described in more detail. The Great Fault crosses the Island from Fomm ir-Rih on the western coast (Figure 4) to the proximity of Madliena Tower on the eastern coast (Figure 5 and Figure 6). The Great Fault forms a fault scarp, which is the most significant topographic feature of the Island. The maximum effect of this Fault can be seen in central areas where the Upper Coralline Limestone on the northern, downthrown side of the Fault, is brought into juxtaposition with the Lower Coralline Limestone.

North of the Great Fault the structure is dominated by the development of horst and graben blocks, bounded by ENE trending normal faults. Such structures are indicated by prominent ridges and valleys, the main units from north to south being Marfa Ridge, Mellieha Valley, Mellieha Ridge, Mizieb Valley, Bajda Ridge, Pwales Valley, Wardija Ridge and Bingemma Valley (Figure 5 and Figure 6). Comino probably represents the exposed part of an otherwise submerged graben to the north of the Marfa Ridge (Pedley et al., 1976).

The structural setting of the Maltese Islands is dominated by two rift systems of different ages and trends (Figure 6). Accompanying faults are exposed at many places along cliffs and are associated with rift faulting (Illies, 1981). The older rift generation traversing the Islands strikes about 50° to 70° to create a basin-and-range or horst and graben structure on western Malta, Comino and eastern Gozo (Figure 5 and Figure 6). The second-generation rift, associated with the Pantelleria Rift (Figure 7), strikes Malta at about 120° and Gozo between 80° and 90°. Rifting mainly originated during the Late Miocene / Early Pliocene, to continue in parts up to the present (Illies, 1981).

The fracture pattern is dominated by two intersecting fault systems which alternate in tectonic activity. A NE-SW to ENE-WSW trending fault, the Great Fault, traverses the Islands and is crossed by a NW-SE trending fault, the Maghlaq Fault (Figure 6), parallel to the Malta trough, which is the easternmost graben of the Pantelleria Rift System (Figure 7). In general the faults, all vertical or subvertical, are part of a horst and graben system of relatively small vertical displacement. Folding is restricted to slump, drag folding and one larger anticlinal structure.

Methods
The research presented in this paper has been undertaken because there is very little knowledge regarding mass movement processes and slope instability along the northern coastline in Malta. In this regard, the work published by Dykes (2002) is an exception. Clay slopes are given particular attention since they dominate the coastal cliffs and are significant in influencing the geomorphology of this particular Region. The study adopts an integrated approach, including geological and geomorphological investigations, geotechnical testing and slope stability assessment. To accomplish these tasks, several techniques have been utilised, as listed below and explained in more detail in the relevant sections.

i. Geomorphological mapping has been undertaken for the northern coast to determine the spatial distribution of coastal features and mass movement processes, and to try and establish a relationship between geology and geomorphology.

ii. Three key sites, representative of the northern coastal region, have been selected to carry out a more detailed field investigation.

iii. At each field site, a representative slope profile was identified to carry out surveying and sample collection for laboratory analysis.

iv. Geotechnical testing was carried out on Blue Clay samples, to determine the physical and mechanical properties of the material and associated behaviour.

v. Slope stability analysis has been performed for the three study sites, simulating different scenarios to determine the critical conditions which influence the stability of slopes.
Figure 5: Map showing the region north of the Great Fault (adapted from Ransley and Azzopardi, 1988).

Figure 6: The tectonic structure of the Maltese Islands (Alexander, 1988).

Figure 7: The system of the Pantelleria Rift traverses the shelf between Sicily and northern Africa. Parallel grabens are observed in Tunisia. The general trend of foreland rifting is about normal to the northward adjacent segment of the Alpine collision front (Illies, 1981).
Mass movement processes along the northern coast

Geomorphological survey

Paskoff and Sanlaville (1978) claimed that the general outline of the Maltese littoral zone has been determined by tectonics and that lithology and advanced karstification have to be considered when studying the coast in detail. In spite of the small size, the Maltese Islands display a large variety of coastal features, including bays, low limestone coasts and cliffs which plunge directly into the sea or are skirted by landslides and wave-cut platforms.

For the purpose of this research a coastal geomorphological survey was carried out north of the Great Fault extending over a distance of about 56.5 kms (Figure 8). This survey was carried out during the spring months of 1999 and 2000. Two maps, scale 1: 10000 were produced from aerial photographs and field mapping, featuring the distribution of coastal landforms, of the Victoria Lines Fault. The survey was performed in this Region because the varied topography provides the opportunity to examine the relationship which exists between structural geology, lithology and landforms, especially at the coastal zone. Moreover coastal mass movement processes are only present in the northern region due to the superimposition of two specific geological formations – Upper Coralline Limestone and Blue Clay. Elsewhere on Malta, the topography and coastal features occur in a less complex structural and geological setting and, from a geomorphological perspective, are not as interesting as the northern region since there is less diversity of landforms. The geomorphological survey provided detailed and innovative information on mass movement processes along the northern coast in Malta which can increase our understanding of coastal processes and landforms in this Region.

Mass movement processes along the coast of Malta, north of the Great Fault, occur mostly on the north-west shoreline (Figure 8) where Upper Coralline Limestone and Blue Clay outcrop adjacent to each other in coastal cliffs. Figure 8 includes a geomorphological map which features the distribution of the different types of mass movement processes which have been identified from the geomorphological survey. According to Varnes (1978) classification (Figure 9), these processes fall under three main categories: slides (Figure 9), falls (Figure 10) and flows (Figure 11). Mass movements predominate on the north-west coast and occur at specific localities on the northern and north-east coasts. Translational slides and rock fall (Figure 1) occur within the Upper Coralline Limestone Formation, whereas earth flows (Figure 1) develop in Blue Clay. Rock fall varies in magnitude from debris to boulder scree and large blocks.

Faulting in the Upper Coralline Limestone plateau (usually 10 m to 15 m high) and basal undermining within the Blue Clay cause blocks of rock to dislodge from the scarp face and fall on the clay slopes below, producing rock fall and landslides. When heavy rainfall occurs, Blue Clay slopes (Figure 11) can become unstable leading to the development of earth flows. When mass movement processes (slides, falls and flows) occur, they invariably change the overall slope form and topography of the northern coastal region, irrespective of the velocity of movement at which they occur. Changes are clearly more visible at high velocities, but slow movements can equally change the morphology of the terrain. Instability is more widespread on the north-west coast where outcrops of Upper Coralline Limestone and Blue Clay are extensive (Figure 8). The north-east coast is more stable as the geological structure is mainly composed of Globigerina Limestone and Lower Coralline Limestone (Figure 8). Due to the limited duration of the field study, it was difficult to undertake observations or quantify any measurements with regards to landslides or rock fall occurring in the Upper Coralline Limestone Formation since movements are slow and require a longer period of time to observe and investigate.

This research focuses on instability in the Blue Clay Formation consisting of unconsolidated material. At the coastal zone Blue Clay features slopes which usually extend from the base of the Upper Coralline Limestone plateau to sea-level. The best examples of clay slopes are found at Gnejna Bay and Il-Qarraba (Figure 11) on the north-west coast. Blue Clay is exposed in most of the localities on the north-west coast while outcrops of this formation are limited to few localities on the northern and north-east coasts. Earth flows become active when clay contains a high water content. This type of mass movement is triggered after heavy and prolonged rainfall events, which frequently occur from October until March in Malta. After the summer drought, which lasts from April until September, Blue Clay loses most of its moisture and becomes very dry. The first rains saturate the clay and fill tension and desiccation cracks with water. The latter develop during the summer months as a result of drying and the associated reduction in volume of the clay. At this stage the Blue Clay would be in a position to absorb water quickly. After prolonged rainfall, the clay becomes fully saturated and starts moving as earth flows. Such a process has also been reported in Dykes (2002).

Geomorphological mapping

The geomorphological survey was also used to identify three ‘type sites’ where slope instability occurs in the Blue Clay Formation. The three selected sites are Gnejna Bay, Ghajn Tuffieha Bay and Rdum id-Delli, all located on the north-west coast (Figure 12). These coastal sites were chosen as they provide the best examples of Blue Clay outcrops at the coast which display slopes extending from the Upper Coralline Limestone plateau to sea-level. At these sites, a more detailed investigation programme, including geomorphological mapping at a large scale (1:1000), surveying, sample collection for material testing and slope stability analysis, was undertaken. The latter enabled a quantitative assessment
Figure 8: Geomorphological map of the northern coast showing the area under study and the distribution of mass movement processes.

Figure 9: An example of a translational slide occurring within the Upper Coralline Limestone on the north-west coast. Usually these slides involve a displacement from the *in situ* material to several metres downslope and in some cases extending to the shoreline.

Figure 10: Rock fall is the most important mass movement process along the Maltese coasts. This process occurs in the Upper Coralline Limestone where blocks are detached from the plateau and fall on the underlying strata.

Figure 11: Where Blue Clay is exposed at the coast, it features slopes which extend from the Upper Coralline Limestone plateau to sea-level. Earth flows are triggered by rainfall during the autumn and winter months.
of the stability of Blue Clay slopes for the north-west coast of Malta where instability could be predicted.

![Diagram](image)

Figure 12: Location of the three field sites along the north-west coast of Malta.

The large-scale mapping extended during the spring months of 1999 and 2000 and included the mapping of the main geomorphological features (such as plateau scarp face, cliff face and shore platform) and processes (such as rock fall, translational slides and earth flows); morphometry of the clay slopes including the slope gradient, shape of the slope (convex or concave) and the smooth changes or angular breaks of slope; hydrology indicated by the presence of stable and active gullies and seepage lines; the presence of vegetation and rubble walls indicating abandoned agricultural practices; and the location of a surveyed slope transect. The Upper Coralline Limestone plateau was also used to determine the inland distance up to where the coastal features were mapped. Figure 13 features an example of the geomorphological map produced for Gnejna Bay. Geomorphological maps were also produced for the other two field sites.

**Slope surveying**

Following the large-scale geomorphological mapping, a representative slope profile (Figure 14) was identified at each site to conduct a more detailed study, first by surveying and then by collecting samples for laboratory analysis. Each transect extended from the base of the Upper Coralline Limestone plateau to sea-level. Another criterion taken into consideration when choosing the slope was that the lateral shears could be identified, in order to be able to clearly define the mass movement feature and distinguish its boundaries. At each of the three sites, the selected transect was surveyed using a Leica TC600 total station laser level. Every change in the topography along the transect resulted in a topographic measurement. Figure 14 shows the cross-sections of the surveyed slopes at the three field sites. Data collected included height above sea-level and horizontal distance from sea-level. Slope gradients were calculated from the readings using the tangent computation. The data regarding the height above sea-level were then reduced from the datum to obtain the actual field measurements. This exercise was undertaken so that the data of the three transects were used to run a computer modelling software (XSTABL) to assess slope stability at each of the three sites.

**Instability in Blue Clay slopes**

Instability in Blue Clay slopes has been examined through material laboratory testing and slope stability analysis. The geomorphological mapping (scale 1:10000) for the northern coast of Malta was used to identify three sites to be representative of the whole region where Blue Clay samples could be collected to conduct detailed laboratory investigations.

**Material testing**

**Collection of clay samples**

Undisturbed clay samples were collected from the surveyed clay slopes at the three field sites from a depth of about 50 cm. Blocks of clay were cut and care was taken to keep the blocks intact. The samples were covered with plastic film and aluminium foil to avoid loss of moisture during transportation, storage and preparation. The samples were then put in plastic boxes (20.5 cm long, 11.0 cm wide and 15.0 cm high) and taken to the laboratory for physical and geotechnical testing. The use of paraffin wax was not necessary as tests were carried out immediately after the samples were collected, to eliminate the problem of loss of moisture.

**Laboratory testing**

During laboratory testing established techniques and procedures (Head, 1980; BS 1377, 1990) were followed. The field moisture content (volumetric water content), bulk density and bulk unit weight (Weighing in Water Method), particle size distribution (Sieving and Sedimentation [Hydrometer Analysis Technique]) and Atterberg Limits (Casagrande Method for the Liquid Limit and Thread Method for the Plastic Limit) were calculated to determine the physical properties of Blue Clay.

Direct shear tests (Shear Box Technique) on undrained samples were carried out to examine the geotechnical properties of stress, strain and shear so that ultimately material strength could be determined. Five tests with different vertical loads ranging from 5 kg to 25 kg were carried out for each site. The horizontal shear force applied on the box was at a constant rate of strain of 1.27 mm/minute. Samples were cut to fit the shear box - 60 mm wide, 60 mm long and 25 mm high, in the form of an intact square block. Readings for both the horizontal displacement, that is the strain and vertical deformation were recorded every 15 seconds. Each test was terminated when the specimen failed, with a time duration ranging from a minimum of 2 minutes to a
Figure 13: A geomorphological map of Gnejna Bay, one of the three field sites along the north-west coast, where a detailed investigation was conducted.


Figure 14: Cross-sections of the surveyed slopes at the three field sites
maximum of 5 minutes 15 seconds. Examination of the samples after testing showed that in most cases a shear plane had developed.

**Physical and geotechnical properties**

Knowledge of material properties provides useful information regarding the processes involved in the formation of geomorphological features. In the case of Blue Clay, analysis of results derived from laboratory testing provides links between the physical properties and geotechnical properties which give an indication of the way soil behaves. Table 2 shows the physical and geotechnical properties of Blue Clay derived from laboratory testing. The results for the field moisture content and bulk density represent the average results. In both cases, tests were performed three times for each field site and the average result calculated. Various similarities and differences can be distinguished between the three field sites. Gnejna Tuffieha Bay exhibits a low bulk density, low cohesion value and high moisture content (Table 2). These properties may indicate greater percolation and high water retention capacities. This leads to an increased earth flow activity. Gnejna Bay and Rdum id-Delli exhibit similar properties. Both sites have lower moisture contents, higher bulk densities and higher cohesion values (Table 2), resulting in an increase in material strength. Three main conclusions regarding the stability of the three field sites can be drawn from physical and geotechnical laboratory data: (1) Rdum id-Delli is the most stable site; (2) Gnejna Bay shows stability with a trend towards instability; (3) Ghajn Tuffieha Bay is the site most prone to instability. The latter conclusion is also supported by the results derived from the study carried out by Dykes (2002) which clearly demonstrate that earth flows at Ghajn Tuffieha Bay are active.

The information derived from laboratory testing can be used to explain geomorphological processes and landforms. Field observations at all three sites highlight the presence of mass movement processes, although these were not operating at the time of geomorphological mapping and sample collection. There is an indication of instability especially at Rdum id-Delli, where earth flows are inactive. Reactivation may be initiated when rainfall starts increasing water content and pore water pressure, leading to unstable conditions. Geomorphological mapping has showed that earth flows develop where Blue Clay outcrops at the base of an Upper Coralline Limestone plateau. They are distinct individual features some having a vegetation cover, whereas others have bare surfaces. Curved back scars and slip surfaces at Rdum id-Delli indicate the presence of deep-seated rotational slides, typical of argillaceous material (Enriquez-Reyes et al., 1990), such as Blue Clay.

Outcrops of Blue Clay are prone to erosion by water during high intensity storms when moisture content increases and the material starts losing strength. Long duration rainfall events saturate bare ground surfaces, resulting in overland flow and surface runoff. Water running on exposed clay erodes the ground surface, leading to the formation of gullies. The presence of desiccation cracks especially at Gnejna Bay and Rdum id-Delli indicates dry conditions, slower rates of movement and more stable conditions.

Blue Clay is an over-consolidated clay since it is overlain by Upper Coralline Limestone and Greensand. Results of geotechnical tests indicating the peak strength parameters are presented in Table 2. Blue Clay has low cohesion values and can be classified as a soft clay. From geotechnical testing of the Blue Clay material, it has been observed that a low clay content contributes to a decrease in material strength. Ghajn Tuffieha Bay has the lowest clay content and lowest cohesion value, whereas Rdum id-Delli has the highest percentage of clay and the highest cohesion value. Gnejna Bay and Ghajn Tuffieha Bay have higher friction angles due to a larger proportion of silt and sand. The shear strength parameters, especially cohesion, differ from those reported in Dykes (2002). However it should be noted that the latter author reports the results of drained shear tests with different loads and shear rate performed on larger samples. Moreover in the case of this study the tests were performed on undrained samples which were collected in spring when the Blue Clay starts losing moisture and becomes dry and crumbly. Rahn (1996) in fact claims that dry clay has low cohesion which increases as moisture content increases until clay reaches the Plastic Limit.

An understanding of shear strength is fundamental to the behaviour of a soil mass and is of major importance for slope stability (Barnes, 1995). Strength determines the ultimate force required to cause failure and is closely controlled by water content. Landslides usually take place during and after rainfall events when there is an increase in moisture content. Values of shear strength and shear stress permit the determination of the Factor of Safety, expressed as the ratio between the two variables (Summerfield, 1991).

**Slope stability analysis**

Slope stability analysis was performed on the previously surveyed Blue Clay slopes (Figure 14) at the three field sites along the north-west coast of Malta. As previously mentioned the selected slopes extend from the base of the Upper Coralline Limestone plateau to sea-level. The predominant mass movement process operating on these slopes is related to earth flows. Table 3 provides the mean gradient characteristics of the three selected slopes, where data are given for the toe area, main section and rear part of each surveyed slope. The slope at Ghajn Tuffieha Bay is the steepest slope (mean slope gradient 19.22°), followed by that at Rdum id-Delli (22.20°) and Gnejna Bay (26.31°). Figure 14 features the profiles of the surveyed slopes at the three field sites.

**Input data**

Since effective stress is a better indicator of soil strength, an effective stress analysis was performed for the purpose
Table 2: Physical and geotechnical properties of Blue Clay. Data compiled by author.

<table>
<thead>
<tr>
<th>Physical Properties</th>
<th>Gnejna Bay</th>
<th>Ghajn Tuffieha Bay</th>
<th>Rdum id-Delli</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field Moisture Content (%)</td>
<td>24.17</td>
<td>41.45</td>
<td>26.80</td>
</tr>
<tr>
<td>Bulk Density (g/cm³)</td>
<td>1.79</td>
<td>1.70</td>
<td>1.79</td>
</tr>
<tr>
<td>Bulk Unit Weight (kNm³)</td>
<td>17.59</td>
<td>16.71</td>
<td>17.53</td>
</tr>
<tr>
<td>Particle Size Distribution (%)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clay (&lt; 2 µm)</td>
<td>44</td>
<td>35</td>
<td>61</td>
</tr>
<tr>
<td>Silt (2 µm – 63 µm)</td>
<td>44</td>
<td>46</td>
<td>29</td>
</tr>
<tr>
<td>Sand (63 µm – 2mm)</td>
<td>12</td>
<td>19</td>
<td>10</td>
</tr>
<tr>
<td>Atterberg Limits</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Liquid Limit (%)</td>
<td>76.00</td>
<td>76.42</td>
<td>79.78</td>
</tr>
<tr>
<td>Plastic Limit (%)</td>
<td>37.79</td>
<td>41.66</td>
<td>36.75</td>
</tr>
<tr>
<td>Plasticity Index</td>
<td>38.21</td>
<td>34.76</td>
<td>43.03</td>
</tr>
<tr>
<td>Liquidity Index</td>
<td>-0.36</td>
<td>-0.006</td>
<td>-0.23</td>
</tr>
<tr>
<td>Consistency Index</td>
<td>1.36</td>
<td>1.006</td>
<td>1.23</td>
</tr>
<tr>
<td>Activity Index</td>
<td>0.74</td>
<td>0.82</td>
<td>0.60</td>
</tr>
<tr>
<td>Geotechnical Properties</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Strength Parameters</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cohesion (kPa)</td>
<td>0.239</td>
<td>0.024</td>
<td>0.658</td>
</tr>
<tr>
<td>Angle of Internal Friction (°)</td>
<td>30</td>
<td>25</td>
<td>22.5</td>
</tr>
</tbody>
</table>

Table 3: Mean gradient characteristics of the surveyed slopes at the three field sites. Data compiled by author.

<table>
<thead>
<tr>
<th>Slope sections</th>
<th>Mean gradient (°)</th>
<th>Slope sections</th>
<th>Mean gradient (°)</th>
<th>Slope sections</th>
<th>Mean gradient (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gnejna Bay</td>
<td>Length of slope: 132.77m</td>
<td>Height of slope: 71.68m</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ghajn Tuffieha Bay</td>
<td>Length of slope: 226.77m</td>
<td>Height of slope: 74.31m</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rdum id-Delli</td>
<td>Length of slope: 118.35m</td>
<td>Height of slope: 44.81m</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Toe area</td>
<td>25.20</td>
<td>Toe area Bulge - 31.20 Flat top - 10.89</td>
<td>Toe area</td>
<td>16.38</td>
<td></td>
</tr>
<tr>
<td>Main section</td>
<td>23.50</td>
<td>Main section 19.34</td>
<td>Main section 22.32</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rear part</td>
<td>35.49</td>
<td>Rear part 23.04</td>
<td>Rear part 27.78</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Entire slope</td>
<td>26.31</td>
<td>Entire slope 19.22</td>
<td>Entire slope 22.20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Angle of internal friction</td>
<td>30.00</td>
<td>Angle of internal friction 25.00</td>
<td>Angle of internal friction 22.50</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4: Calculated Factor of Safety values using the Simplified Bishop Method (1955). Data compiled by author.
of this research. In this type of analysis the effective strength parameters are evaluated using appropriate laboratory tests, computing the effective normal stress along the failure surface and computing the shear strength using the Mohr-Coulomb equation (Coduto, 1999). The pore pressure is specified as an independent variable (Nash, 1987). In practice this is achieved if the failure mass of soil is divided into a number of slices, such as with the Bishop Method of Slices (1955). The latter Method was used for the analysis of Blue Clay slopes because all the required parameters can be measured in the field and in the laboratory at each field site. Slope geometry and material geotechnical properties have been determined in previous geomorphological and geotechnical investigations and used for the stability analysis. All input variables (slope geometry and material strength properties including cohesion, angle of internal friction, and bulk unit weight) have been kept constant, except for one parameter, that is the pore pressure ratio (ru).

The pore pressure has been specified as an independent variable since an effective stress analysis was performed. The pore pressure ratio (ru) value was used in this analysis since pore water pressure was not measured in the field due to lack of instrumentation and because the precise distribution of pore pressures is unknown. The pore pressure ratio represents overall pore pressure conditions in Blue Clay slopes and is the only variable parameter for the whole analysis. This parameter was changed to study its effect on the stability of Blue Clay slopes by identifying the critical phreatic conditions at which the slopes fail. For the first analysis at each site the pore pressure ratio is set at 0.0 (Table 4). This ratio increases by a factor of 0.05 each time a new analysis is performed until the ratio generates a calculated Factor of Safety which is less than unity, indicating a state of instability. At this point other analyses were not performed, since the transition between stability and instability is established. Results are presented in Table 4 where differences can be observed between the three sites indicating that instability is reached at different pore pressure ratio values.

### Slope stability modelling

The input data were used to run a series of slope stability models utilising XSTABL software. XSTABL, version 5.0 was developed by Interactive Software Designs, Inc (USA) in 1994 using Microsoft FORTRAN 5.1 compiler, Microsoft Macro Assembler (MASM 5.1) and screen graphics and printer software tools from MicroGlyph Systems (USA) and Jewell Technologies, Inc. (USA) (Sharma, 1994).

XSTABL is a fully integrated slope stability analysis program which permits the development of slope geometry. It consists of two interactive but separate parts: a data preparation interface and a slope stability analysis. The program uses the Method of Slices to perform a two-dimensional Limit Equilibrium analysis to compute the Factor of Safety for a slope according to General Limit Equilibrium (GLE) Method, Janbu’s Generalized Procedure of Slices (GPS), Simplified Bishop and Simplified Janbu. From the input data, Factor of Safety values (Table 4) corresponding to the most critical surfaces along which failure can occur, were calculated using the Bishop Method (1955) of analysis.

Stability depends on a variety of parameters, such as cohesion, angle of internal friction, gradient, bulk unit weight and pore water pressure. It can be concluded from stability analyses that the investigated slopes are very sensitive to changes in the phreatic surface and groundwater conditions simulated by changes in the pore pressure ratio. In all cases, as the pore pressure ratio increases the Factor of Safety decreases leading to instability (Table 4). High pore water pressures can be produced from rainfall, resulting in a decrease in shear resistance and consequently slope failure (Cooke and Doornkamp, 1990). It is important to note that Blue Clay is an impermeable material. Consequently when it becomes saturated especially after the dry summer months (April to September), it will be able to retain a significant amount of water. During the rainy season (usually October until March) additional rainwater causes the material to swell and increase in volume, especially at the surface layer. This impermeable surface prevents further infiltration of water and causes the clay to become plastic and unstable. Such a situation is further exacerbated by the water penetrating through the permeable Upper Coralline Limestone, and flowing on the Blue Clay below, resulting in runoff.

Various results of the Factor of Safety are presented for each site in Table 4 since several analyses were performed. Factor of Safety values show significant differences between the three sites. The transition between stability and instability is reached at different pore pressure ratios. The slope at Gnejna Bay remains the most stable slope at a high pore pressure ratio. This is followed by Ghajn Tuffieha Bay and Rдум id-Delli. Factor of Safety values decrease in this order. Modelling proved to be useful as it determines the prevalent conditions at each of the three sites and rigorously predicts instability.

Due to its high percentage of clay and silt content, Blue Clay has a high swell capacity, lower permeability, is more compressible and consolidates over a longer period of time under load. These characteristics can also be related to the mineralogy of the Blue Clay material. However mineralogical analyses were not carried out on the tested samples, therefore this can only constitute an assumption. Such properties enable Blue Clay to absorb a significant amount of water before soil reaches a liquid state, showing that instability occurs at high pore water pressure. This is also confirmed by Factor of Safety values calculated from the stability analyses (Table 4). At Gnejna Bay and Ghajn Tuffieha Bay instability is reached when the pore pressure ratio is high, resulting from a fully saturated soil. Rдум id-Delli produces the lowest Factor of Safety values and the transition between stability and instability is reached before the other two sites. Gnejna Bay generates the highest Factor of Safety due to its high percentage of clay and silt content, Blue Clay has a high swell capacity, lower permeability, is more compressible and consolidates over a longer period of time under load. These characteristics can also be related to the mineralogy of the Blue Clay material. However mineralogical analyses were not carried out on the tested samples, therefore this can only constitute an assumption. Such properties enable Blue Clay to absorb a significant amount of water before soil reaches a liquid state, showing that instability occurs at high pore water pressure. This is also confirmed by Factor of Safety values calculated from the stability analyses (Table 4). At Gnejna Bay and Ghajn Tuffieha Bay instability is reached when the pore pressure ratio is high, resulting from a fully saturated soil. Rдум id-Delli produces the lowest Factor of Safety values and the transition between stability and instability is reached before the other two sites. Gnejna Bay generates the highest Factor of Safety.
values for all three sites. Ghajn Tuffieha Bay also produces high Factor of Safety values, although they are significantly less than those at Gnejna Bay (Table 4).

The low cohesion values typical of the three sites result from Blue Clay being a dry soil with moisture contents below the Plastic Limit (Rahn 1996). It is interesting to note that Rдум id-Delli which has the highest cohesion value (Table 2), indicating an increase in material strength, produces the lowest Factor of Safety values (Table 4). It can be concluded that although the material is competent it becomes unstable more quickly than expected. In fact earth flow activity was observed only at this site, suggesting that mass movement processes are present although inactive during dry periods. Factor of Safety values (Table 4) and geotechnical data (Table 2) suggest an inverse situation for Ghajn Tuffieha Bay. Although the material at this site shows a decrease in strength, it remains stable even under saturated conditions. Instability is reached when the pore water pressure is exceptionally high to be sustained by the material. Gnejna Bay is the most stable site, where instability is reached at a higher pore pressure ratio than at the other two sites.

Conclusions

Mass movement processes occurring along the northern coast of Malta have been described in detail and the association between tectonics, structural geology and geomorphology explained. Previous coastal studies (for example Guîcher and Paskoff, 1975; Paskoff and Sanlaville, 1978; Ellenberg, 1983; Paskoff, 1985) have dealt with the description of coastal landforms and related processes, but were not specifically concerned with mass movement processes and slope instability. In this sense, this study provides original results that increase our knowledge of coastal processes in Malta.

The geomorphological survey undertaken during the spring months of 1999 and 2000 allowed the identification of different types of mass movement, including slides, falls and flows. Mass movement and slope instability processes invariably occur where Upper Coralline Limestone and Blue Clay outcrop adjacent to each other in coastal cliffs and are predominant on the north-west coast where outcrops of both geological formations are extensive. The main factors controlling these processes include faulting in the Upper Coralline Limestone plateau and basal undermining within the Blue Clay which cause blocks to dislodge and fall, producing rock fall and landslides. Heavy rainfall triggers movement and instability of Blue Clay slopes which can develop into earth flows.

The geomorphological survey was used to identify three ‘type sites’ where slope instability occurs in the Blue Clay Formation. At these sites, a more detailed investigation programme was undertaken, including large scale geomorphological mapping (1:1000), surveying, sample collection for material testing and slope stability analysis. Three main conclusions regarding the stability of the three field sites can be drawn from physical and geotechnical laboratory data: Rдум id-Delli is the most stable site; Gnejna Bay shows stability with a trend towards instability; Ghajn Tuffieha Bay is the site most prone to instability. Slope stability analysis, using the Bishop Method (1955) of analysis, have yielded different Factor of Safety values corresponding to the most critical surfaces along which failure can occur. The investigated slopes are very sensitive to changes in the elevation of the water-table and groundwater conditions as simulated by changes in the pore pressure ratio. The transition between stability and instability is reached at different pore pressure ratios; the slope at Gnejna Bay being the most stable and that at Rдум id-Delli the least stable.

Although this study has considered coastal mass movement processes in detail, the issue of hazards associated with these processes has not been specifically investigated in this study. Currently, other investigations are being undertaken which will evaluate the vulnerability to hazard and provide recommendations on risk analysis and management if the coast is further developed in such a way that mass movement processes can represent a threat to life and property.

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References


