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Landsliding on the south east coast of the Isle of Wight: nature, characteristics and causes

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Abstract

This comprehensive report conveys the nature, characteristics and causes of landsliding along the south east coast of the Isle of Wight. Landsliding is a major geohazard worldwide and is a major land shaping process on the Isle of Wight especially along its coastline and the island provides a unique opportunity to study this process. This report provides information and data on landsliding in an area of the island which hasn't received extensive attention compared to other areas such as Ventnor. The report displays a combination of field data involving geological, lithological and geomorphological data and laboratory data in the form of atterberg limits and shear strength parameters. The findings of this report show that the majority of the study area is highly susceptible to landsliding and the lithology and structure of the area is strongly influencing the type of movement involved in a landslide. The type and nature of the geology and lithology of the area are the major preparatory factors allowing landsliding to occur but the triggering mechanisms in the area are inferred to be rainfall and marine processes. This report also highlights variability of the physical properties of failed material and that the material is highly susceptible to new or repeated failures due to its reduction in shear strength. The findings of this report have pronounced implications for the future of the area due to the predicted future changes in climate and rise in sea level and landsliding is predicted to be a continual process shaping the study area and thus a continual geohazard on the island.

Contents

Chapter one: Introduction

Landsliding is a worldwide natural hazard and is responsible for considerable loss of life and damage to property each year (Hong et al. 2007). In Great Britain landsliding can be seen as potentially the most common geohazard, apart from flooding, but with less extreme topography and limited tectonic activity Great Britain has a uniquely different landsliding regime to many other countries in the world (Foster et al. 2011). In the mid 1980's a landslide database was compiled by the government department of environment (Jones and Lee, 1994) which has since been incorporated into and replaced by the British Geological Survey National Landslide Database (Pennington et al. 2009; BGS, 2013a). This new database was compiled due to a lack of knowledge on landsliding in Great Britain, in particular, their nature and distribution (Foster et al. 2008). It holds over 15 thousand records (Foster et al. 2011) and is the most comprehensive source of information on landslides in Great Britain (Pennington et al. 2009). Thus, landslide research, like this project, will help to improve the knowledge and data on the nature and distribution of landsliding in Great Britain. Landsliding is a common occurrence on the Isle of Wight and provides the perfect opportunity to study this process. The island consists of active landslides that are mostly occurring along the coast, providing a major challenge to coastal management (Mcinnes et al. 1998), but also consist of past relict landslides such as those at St. Catherine's and Appuldurcombe (BGS, 2013b). The island is famous for its landsliding especially at Ventnor (e.g. Risknat, 2013a; 2013b; 2013c; 2013d) but apart from Jenkins et al. (2011), little study has been conducted on less well known areas of the island. This is mostly due to the fact that studies are carried out on hazards where they pose a direct threat to the population or infrastructure or in response to a hazard event. Thus, areas along the coast of the isle of Wight provide the unique opportunity to study landsliding that have previously had little study.

Landsliding involves the movement of a mass of rock, earth or debris down a slope (Cruden, 1991). The main types of landslides are fall, slides, topples, flows and complex and these refer to the movement that is involved in the landslide (Cruden and Varnes, 1996). Each has their own characteristics and style which are explained by Varnes (1978) and Cruden and Varnes (1996). There are numerous factors that can cause a landslide and as suggested by Pospecu (2002) they should be considered as factors that prepare the conditions for failures, such as geology, and factors that actually trigger a landslide such as rainfall (e.g. Iverson, 2000) or earthquakes (e.g. Chen et al. 2012).

1.1 Geology and geomorphology of the study area

The study area consists of a 5km stretch along the east south east coast of the island, from Yaverland to Bembridge foreland (Figure 1.1, 1.2). The area falls where the complete geological succession of the Isle of Wight occurs and thus the greatest change in geology occurs (Figure 1.3), which was a major reason for why this area was chosen for study as it could be seen what effect the different geologies have on landsliding in the area. The island consists of a geological succession of early Cretaceous to early Oligocene age strata (Figure 1.3) with some Pleistocene cover but with the absence of the Neogene and falls into the Wessex-channel basin (Insole et al. 1998).

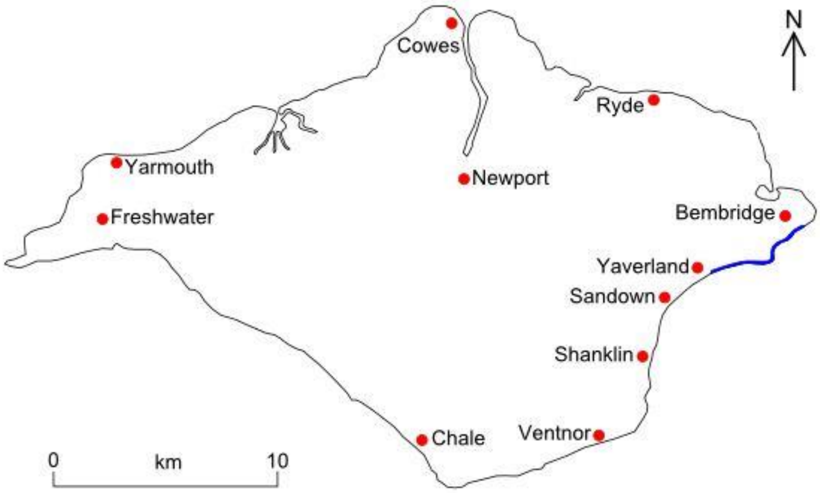


Figure 1.1 Isle of Wight, showing location of study area (shaded blue).

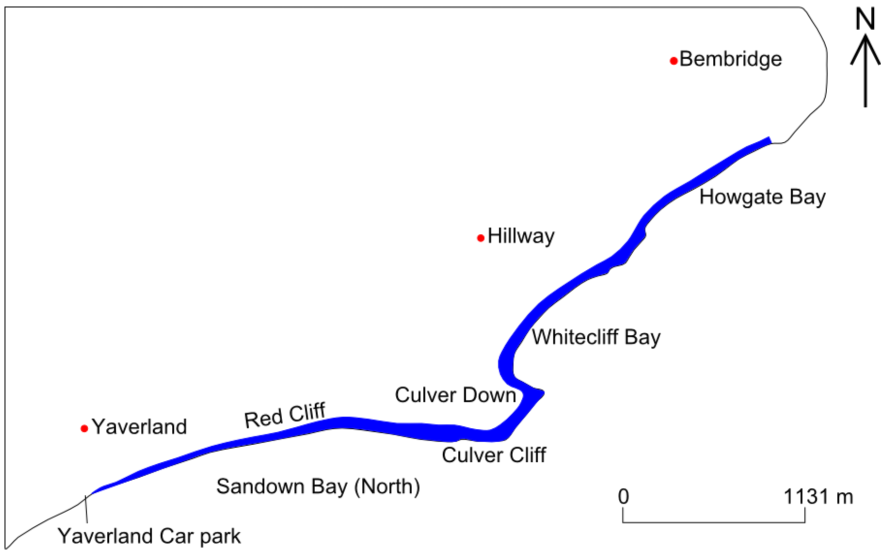


Figure 1.2 Study area (shaded blue) showing key locations.

The oldest rocks on the island belong to the Wealden group (c. 140-126 Ma) (Booth and Brayson, 2011) and outcrop solely in the south of the island and in the study area (Figure 1.3). These rocks are brought to the surface in the cores of two asymmetric anticlines; Brightstone anticline in west and Sandown anticline in east (Figure 1.3) (Insole et al. 1998). The southern limbs of both of these folds dip gently southwards but the northern limbs are much steeper and vertical in places (Insole et al. 1998). In the north of the island the younger Palaeogene (65-23 Ma) strata exist forming a low-lying, gently sloping topography (Booth and Brayson, 2011). Hopson (2011) provides a detailed description of the geological history of the Isle of Wight which is beyond the scope of this paper. The island consists of a prominent east-west trending Chalk downlands, which forms an elevated ridge creating a spine across the island (Figure 1.3) (Booth and Brayson, 2011). This ridge is the expression of the monocline (Figure 1.3), formed along the northern limb of the asymmetric Brightstone and Sandown anticlines (Jenkins et al. 2011). It also controls the formation of steep chalk cliffs (Jenkins et al. 2011) which exists in the study area and the majority of the study area consists of cliffs with varying heights. The problem with the Cretaceous and Palaeogene strata of the island is that they are mainly composed of relatively soft, often poorly lithified sedimentary rocks, which makes them highly susceptible to landsliding (Jenkins et al. 2011) and with the varying geomorphology, discussed in detail by Booth and Bryson (2011), of the island combined with its structural geology (Figure 1.3); the study area provides a unique environment for landsliding to occur.

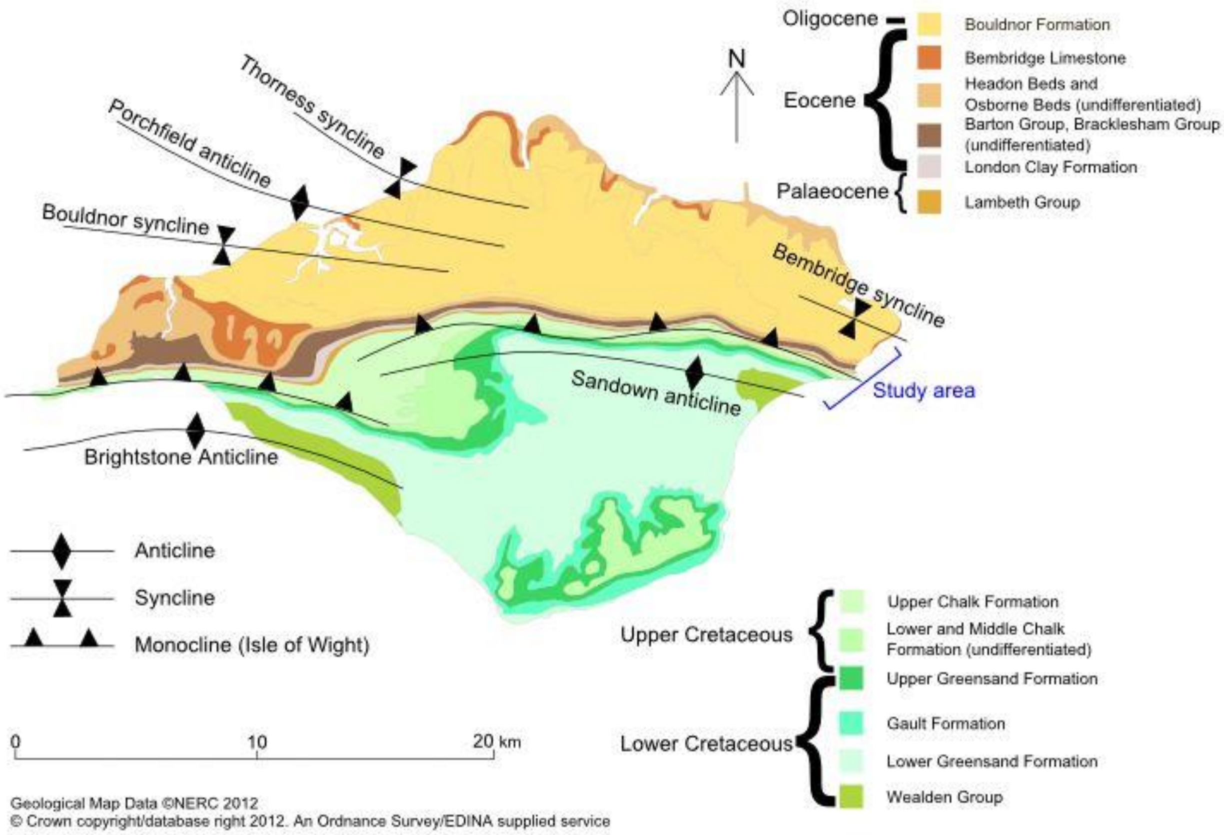


Figure 1.3 Geological map of the Isle of Wight. Study area is indicated by blue bar. Structural geology obtained from Insole et al. (1998) and Hopson (2011).

It is the aim of this study to determine the nature, characteristics and causes of landsliding along the south east coast of the Isle of Wight. The objectives are to analyse and assess to what extent the geology, lithology, topography and geomorphology is having on landsliding in the area; to identify which factors are preparing the conditions for landsliding in the area and to identify factors that could be triggering landsliding in the area.

Chapter two: Methods and Rationale

Desk studies, fieldwork and laboratory work were used to collect data are on landslide in the study area, which are typically used in landslide investigations (Carrara et al. 2003). Remote sensing used Google Earth Pro, utilising its historical imagery in order to see how the cliff line and landsliding has evolved in the study area, which could then be related to lithology. It was also used as a means to collect more data on landslides such as their total length. Field work was conducted from May 27th to 16th June 2012 involving a range of methods. Firstly, an overview of the lithological change of the cliff section was conducted involving lithological descriptions, thickness of changes using a TruPulse (electronic distance measurer) and sketches of the cliff line were produced showing how the lithology changes spatially, which were later reproduced to scale. At the same time pocket penetrometers were used to determine the undrained strength of the cohesive soils in the area. For the rock types, an N type Schmidt hammer was used as a relative indicator of the strength of the rock material (Selby, 1980). Once this was completed, cliff heights and profiles of the cliff slopes were obtained using the TruPulse. The points at which this data were collected were determined based on the morphological change of the cliff line especially where landslides occurred and did not occur. The locations of these points were recorded using a Geo XH Trimble GPS. A landslide database was then conducted of the study area recording the location of the landslides using the Trimble, measurements of the dimensions of the landslide were taken using the TruPulse and general descriptions and inferred movement type were noted. Areas consisting of landslides consisting of the same movement type were grouped into zones for ease of data collection. This would later form the basis of a landslide inventory for data analysis.

After collecting data of the overview of the study area, more detailed analyses were conducted on the landslides. One landslide from Sandown Bay and one from Whitecliff Bay were chosen for detailed study in order to gain further insight into what could be causing the landslides in both areas and also so a comparison could be made between the two areas. The two landslides that were chosen were picked to represent the most common type of landslide that was occurring in the respective areas and thus an understanding could be made of what is causing the similarities or differences. This involved geomorphological mapping (Bishop et al. 2012) of the landslide and followed the approach set out by Fookes et al. (2007). Detailed profiles were taken of the surface of the landslide taken across the landslide and from the toe to the back of the landslide. Samples were then taken from the landslide and sealed in an air tight bag for analysis back in the laboratory, so that the physical properties of the materials involved in the landslide could be determined to see what affect they might be having on the landslides. These were determined using Atterberg limits which determine the plastic and liquid limits of the soil samples, which can then be used to calculate the plasticity index and liquidity index. These limits were determined following the British standard method BS 1377: Part 2 (1990); the liquid limit follows the cone penetrometer method. Moisture content was also determined following BS 1377: Part 2 (1990). The sample collection was strategic in the form they were taken based on the morphology of the landslide i.e. back scar, recently active area, in order to see how the physical properties of the material varied across the landslide. The undrained shear strength of the in situ material from which the samples were taken were determined in the field using a field, hand shear vein (Barnes, 2010) in order to be related to its physical properties and to see how it changes spatially.

A direct shear box test was used to determine shear strength parameters of the soil samples to give a relative indication of slope stability and the test followed the approach set out by Head (1982). Due to the very fine nature of the soils, particle size analyses was conducted to see if there is any relationship between the size fractions and atterberg and shear box tests. The samples were described using Eurocode 7 classification which can be found in Norbury (2010), Eurocode 7 terminology is also used throughout the report. Soils and rocks are referred to in terms of engineering geology.

In addition the terminology used throughout this report follows that of Varnes (1978) and Cruden and Varnes (1996) for movement types, landslide features etc., which is similarly adopted by the BGS (2013c).

Chapter three: Results

3.1 Landsliding in the study area

The majority of landslides in the study area have a Complex movement type with Fall and Flow type landslides being the next dominant (Table 3.1). The most dominant type of movement involved with Complex landslides is flow type with Translational (planar) being the next most dominant (Table 3.2).

Table 3.1 Main movement type and amount occurring in the study area.

Landslide type	Number of landslides
Complex	27 **(39.1%)**
Fall	17 **(24.6%)**
Falls/topple	2 **(2.9%)**
Flow	12 **(17.4%)**
Multiple Rotational	1 **(1.4%)**
Single Rotational	6 **(8.7%)**
Translational (planar)	4 **(5.8%)**
Grand Total	**69**

Table 3.2 Main movement types occurring in Complex landslides.

Landslide type	Number of landslides
Flow	11 **(40.7%)**
Multiple Rotational	1 **(3.7%)**
Single Rotational	6 **(22.2%)**
Translational (planar)	9 **(33.3%)**
Total	**27**

On the stretch of coastline from Whitecliff to Bembridge there are more Flow type landslides occurring than along the stretch of coastline from Yaverland to Culver cliff (Figure 1.2, Table 3.3). For the main type of movements occurring in complex landslides, flow types are most commonly occurring along the coastline from Whitecliff Bay to Bembridge whilst single rotational type landslides are more commonly occurring from Yaverland to Culver cliff (Table 3.4).

Table 3.3 Main movement types occurring along both coastlines. Numbers in brackets

Landslide type	Whitecliff to Bembridge	Yaverland to Culver Cliff	Total
Complex	15 (5) **55.6%**	12 (4) **43.4%**	**27**
Fall	8 **47.1%**	9 (1) **52.9%**	**17**
Falls/topple	0	2 (2) **100%**	**2**
Flow	11 (2) **91.7%**	1 **8.3%**	**12**
Multiple Rotational	1 **100%**	0	**1**
Single Rotational	3 (2) **50%**	3 (1) **50%**	**6**
Translational (planar)	2 **50%**	2 **50%**	**4**
Total	**40 (9)**	**29 (8)**	**69 (17)**

Table 3.4 Main movement types occurring in Complex landslides along both coastlines. Numbers in brackets indicate the amount that were categorised into zones.

Landslide type	Whitecliff to Bembridge	Yaverland to Culver Cliff	Total
Flow	10 (5)	1(1)	**11**
Multiple Rotational	0	1	**1**
Single Rotational	1	5 (1)	**6**
Translational (planar)	4	5 (2)	**9**
Total	**15 (5)**	**12 (4)**	**27**

The Fall type landslides seen at Culver Down (Whitecliff) (Figure 3.1 & photo 3, Figure 3.12) show an accumulation of rocks at the base of the cliff / slope, which can vary in size (see landslide inventory; appendix C). The flow type landslides in Whitecliff Bay have a typical channel shape to them which then expands at the front in a lobate structure (Figure 3.2). Complex landslides with flow as the main movement types are similar but due to there being many converging flows the lobate form is lost for this particular landslide (Figure 3.3).

Figure 3.1 Rock fall (2) at Culver down (Whitecliff), person circled in red for scale.

Figure 3.2 Flow type landslide (6) in Whitecliff Bay (south), person for scale.

Figure 3.3 Complex landslide with main type of movement (25) being flow type (Whitecliff Bay).

Photo 26 (Figure 3.12) shows a larger flow with a series of active flow channels within it. All the flows also show a zone of accumulation at the front of the landslide. The translational (planar) landslides have a U-shape to them (Figure 3.4) which is also seen in the complex landslides with translational (planar) as the main movement type (photo, 9 & 11, Figure 3.12).

Figure 3.4 Cross-sectional shape of a Translational (planar) landslide (16) in Whitecliff Bay (south).

Rotational slides in the area have a distinct mound shape and a distinct back scar (photo 12, Figure 3.12) whilst the multiple rotational landslide in Whitecliff Bay (Figure 3.12; 38) have a stepped form to it.

The single rotational slides in Sandown Bay have a similar form to the ones in Whitecliff with a mound shape created at the front of the landslip (Figure 3.5) and a distinct back scar as seen on a complex landslide that has a rotational slide as the main movement type (photo 9, Figure 3.11).

Figure 3.5 Shallow single rotational landslide (1) at Yaverland. 40L back pack for scale.

The translational (planar) slides in Sandown Bay are different to the ones in Whitecliff Bay (Figure 3.6); the U-shape form is lost, except possibly at the back of this landslide where the failure originated from, they also have a mass of material accumulating at the front of the landslide that has not rotated.

Figure 3.6 Shallow Translational (planar) landslide in Sandown Bay, failure occurring near top of cliff (2). 40L back pack for scale.

This is also seen for the complex landslides with a main translational (planar) movement type (photo 5, Figure 3.11). The complex landslides with flow as the main movement type show distinctive channels where the material has flowed and then displaced material accumulating at the front of the landslide, spreading out and forming a lobe (Figure 3.7).

Figure 3.7 Flow type landslide in Yaverland (6).

The fall type landslides in Sandown Bay are similar to that in Whitecliff Bay showing an accumulation of rocks at the base of the cliff (Figure 3.8 & 24, Figure 3.11).

Figure 3.8 Fall type landslide at Red cliff (19). Person for scale and 40L back pack.

All the fall type landslides in the area are occurring on steep cliff type profiles (Figure 3.9). The flow, translational (planar), complex (flow) and complex (translational (planar) all have similar profiles that are generally straight with a slight convex part at the bottom and concave part at the top (Figure 3.9). The single rotational and complex (single rotational) profiles are similar in that they have a major convex followed by concave part to their profiles (Figure 3.9). The multiple rotational and complex (multiple rotational) are similar to the single rotational profiles but they have at least two segments to their profiles which are convex followed by concave (Figure 3.9).

3.2 Geology, lithology and landsliding in the study area

The area of study shows that nearly all (98.5%) of the landslides involved bedrock geology (Table 3.5). Only a single superficial geology was involved solely with a landslide (Table 3.5). The study area shows great geological variation (Figure 3.10) and even greater lithological change (Figure 3.11 & 3.12). The majority of landslides in the area involved just a single geology and Complex type landslides were involved the most with two geologies (Table 3.6). 41.4% of the landslides in the study area involved a single lithology, 42.6% involved two lithologies and 16.2% involved three lithologies (Table 3.6). The majority of Complex landslides involved two lithologies, whereas the majority of Fall and Flow type landslides involved a single lithology (Table 3.7).

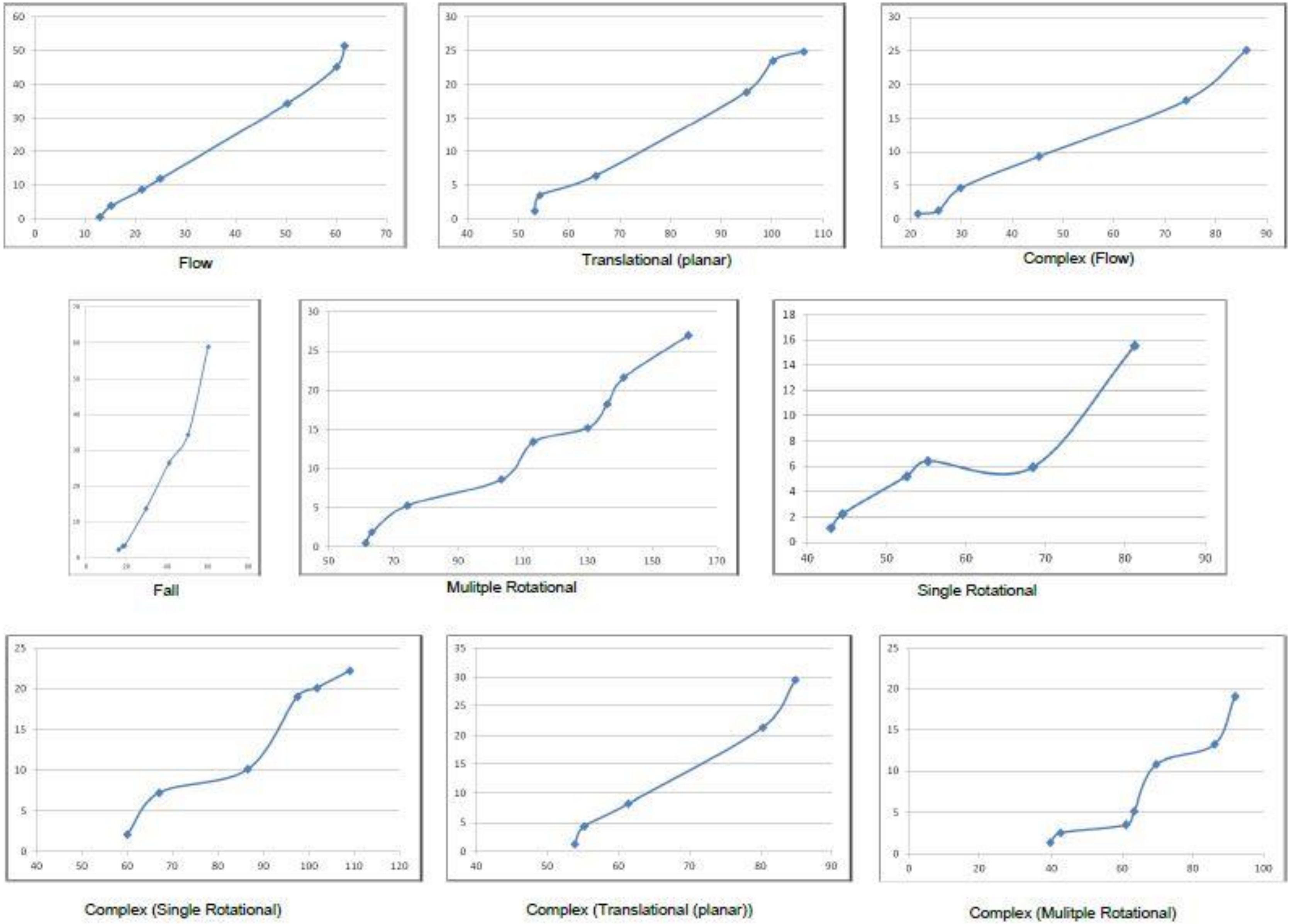
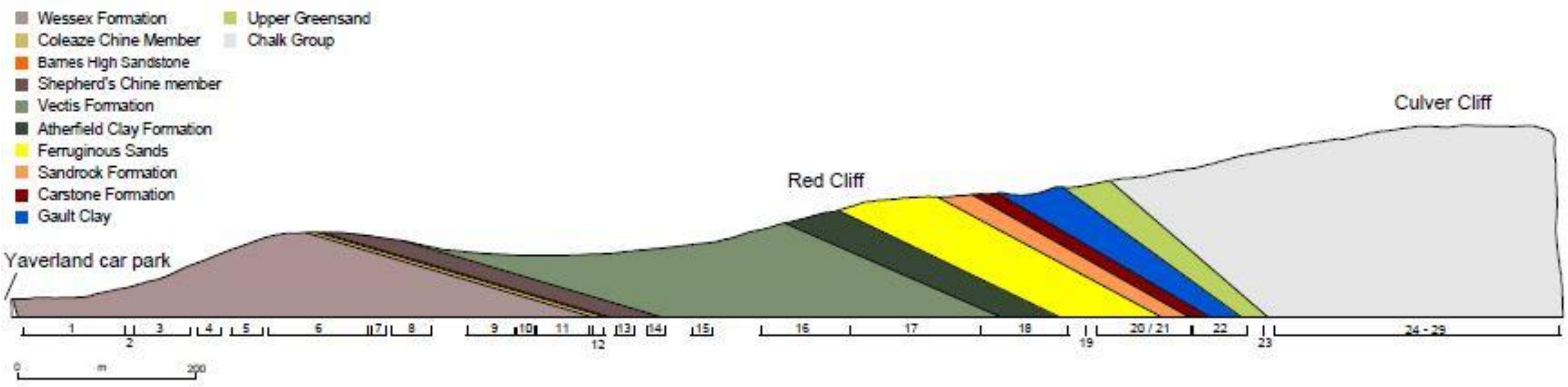
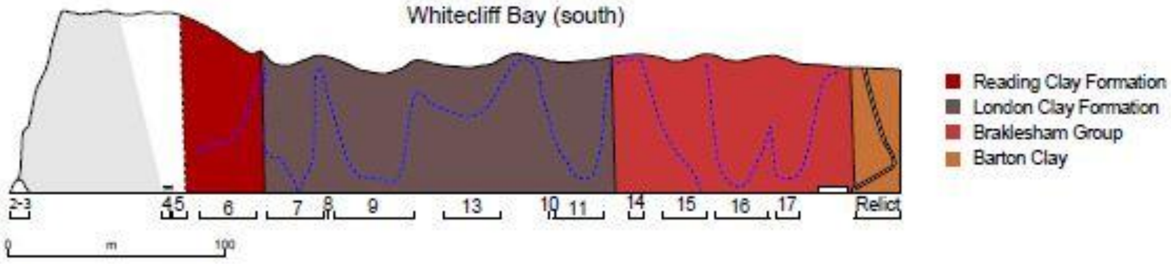


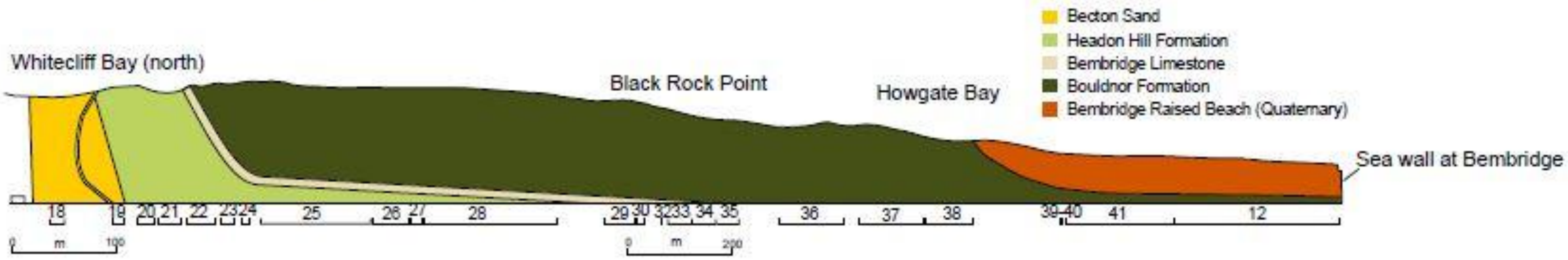
Figure 3.9 Representative profiles of the different type of landslide occurring in the study area. Profiles were collected with the help of Liam Lockwood.



Cliff view of Sandown Bay (North) from Yaverland carpark to Culver cliff. Chalk is not to the same scale.



Cliff view of southern Whitecliff Bay.



Cliff view from northern Whitecliff Bay to start of the sea wall at Bembridge.

Figure 3.10 Change in the geological succession in the study area (produced with the help of information from Insole et al. (1998)).

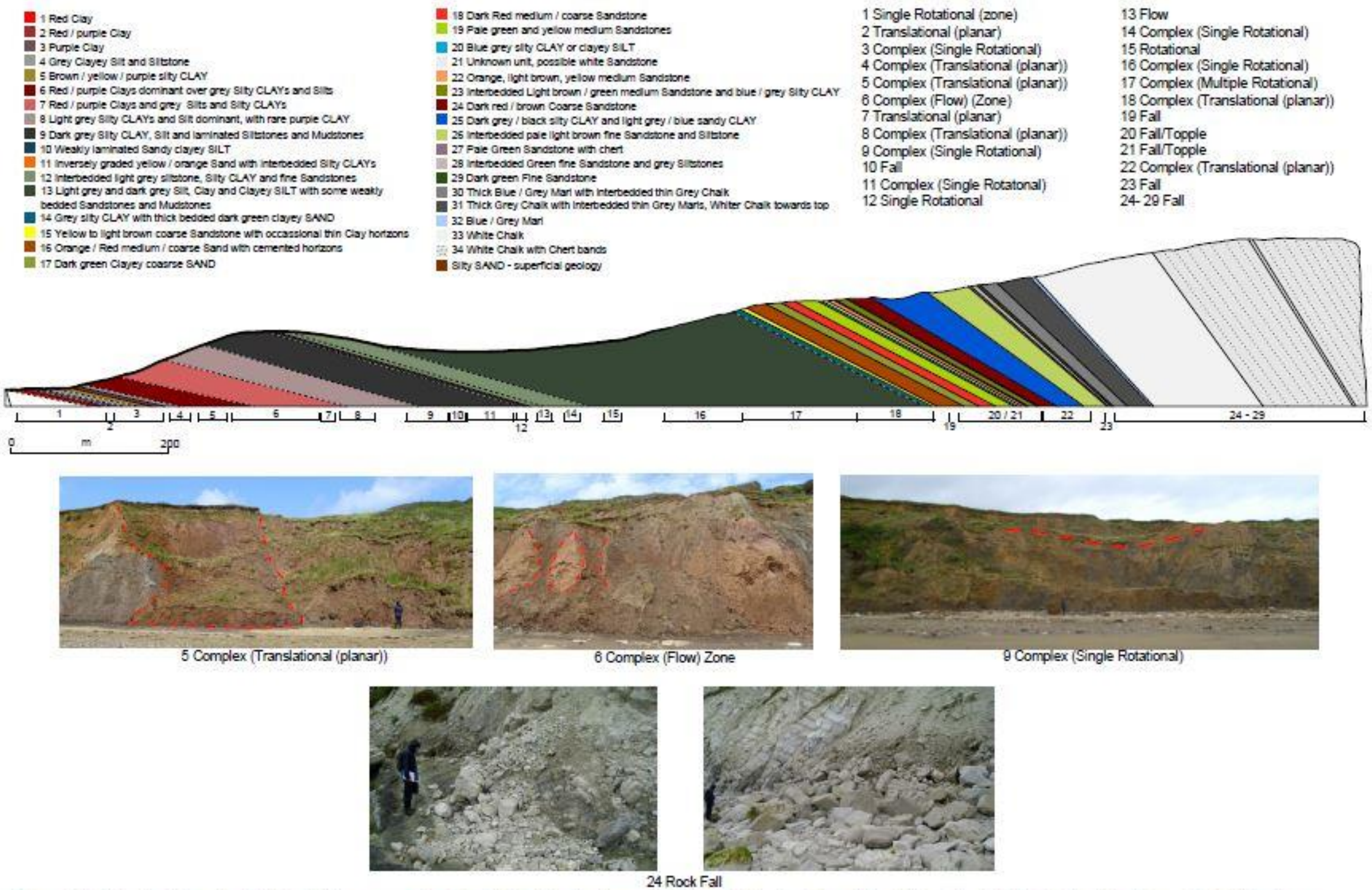


Figure 3.11 Cliff sectional view showing lithological changes occurring in the cliffs from Yaverland car park to Culver cliff (Sandown Bay, north) and the location of the identified landslides. The vertical height has been exaggerated. Chalk cliffs are not to the same horizontal scale. The numbers correspond to landslides which can be found in the landslide inventory located in the appendices. Numbers under the photographs correspond to the numbers located on the cliff views.

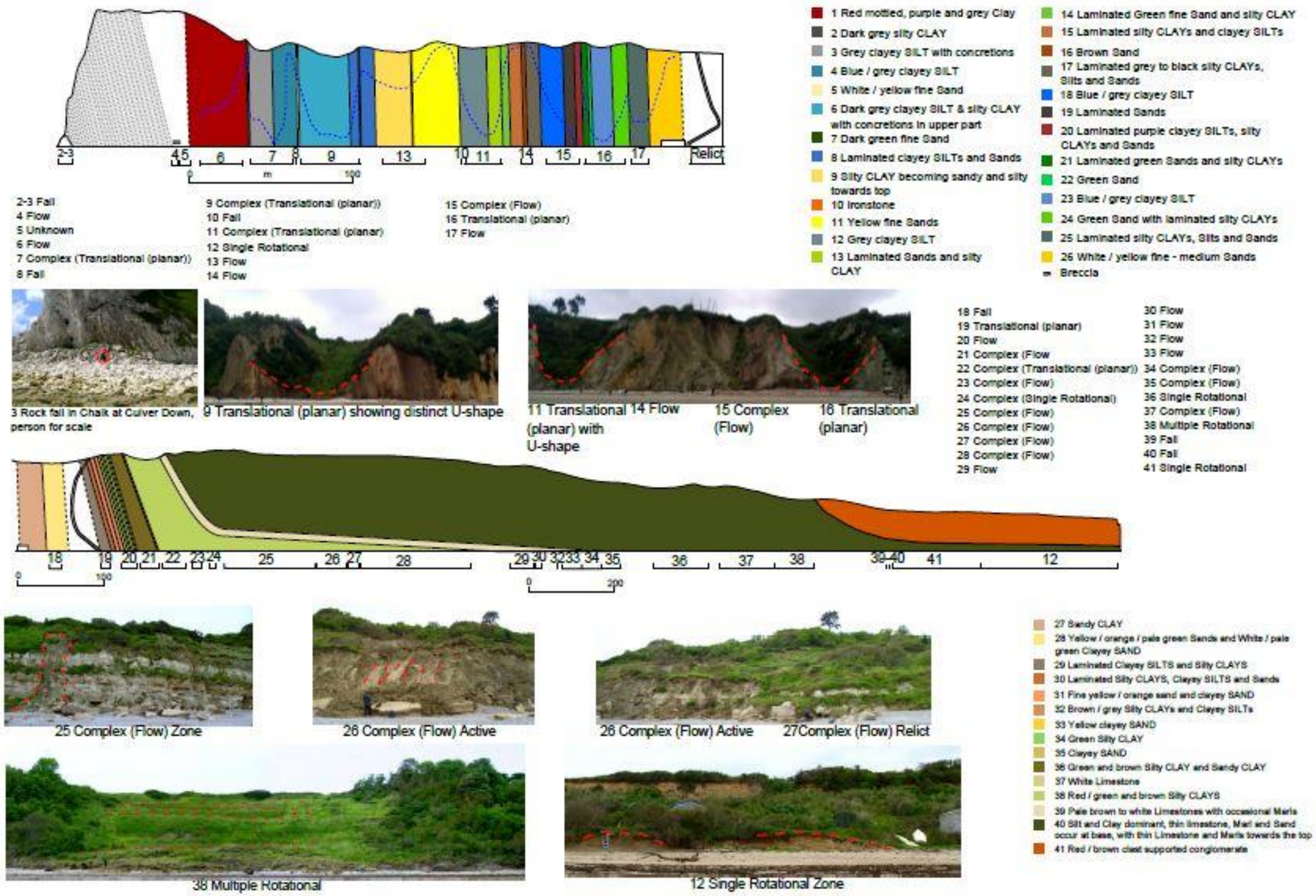


Figure 3.12 Cliff sectional views showing lithological changes that make up the cliff sections from Culver Down to Bembridge and the location of the identified landslides. The top cliff view is from the Chalk cliffs at Culver Down to the southern most Cafe. The bottom cliff view is from the northen most cafe to just before the Bembridge Foreland where the sea wall starts. In both views the vertical height has been exaggerated. The numbers correspond to landslides which can be found in the landslide inventory located in the appendices. Numbers under the photographs correspond to the numbers located on the cliff views. Areas left white were obscured.

Table 3.5 The number and type of landslides involved with either a superficial or bedrock geology. One landslide had unknown lithology involved with a landslide.

Movement Type	Superficial Geology	Bedrock Geology	Superficial and Bedrock Geology
Complex	1	21	5
Fall	0	17	0
Fall/Topple	0	2	0
Flow	0	11	0
Multiple Rotational	0	1	0
Single Rotational	0	5	1
Translational (planar)	0	3	1
Total	**1 (1.5%)**	**60 (88.2%)**	**7 (10.3%)**

Table 3.6 The number of geologies involved with landslide type.

	Single Geology	Two geologies
Complex	17	10
Fall	16	1
Falls/topple	2	0
Flow	11	0
Multiple Rotational	1	0
Single Rotational	3	3
Translational (planar)	4	0
Total	**54 (79.4%)**	**14 (20.6%)**

Table 3.7 The number of different lithologies involved with the different types of landslides.

Movement Type	One Lithology	Two Lithologies	Three lithologies
Complex	6	18	2
Fall	10	5	2
Fall/Topple	1	1	0
Flow	6	1	5
Multiple Rotational	1	0	0
Rotational	3	2	1
Translational (planar)	1	2	1
Total	**28 (41.1%)**	**29 (42.6%)**	**11 (16.2%)**

3.3 Geology and landslide type

The majority of fall type landslides are occurring in the Chalk group, whilst complex and flow type landslides are occurring in the Wessex formation and Bouldnor formation respectively (Figure 3.13). The Bouldnor formation also shows the greatest variation in landslide types occurring within it (Figure 3.13). The majority of the geologies in the area exhibit either one or two landslide types (Figure 3.13). The Bouldnor formation and the Bembridge limestone are most commonly involved with complex landsliding when there are two geological units involved with landsliding (Figure 3.14). Each combination of geological unit exhibits only a single type of movement except for the

Wessex formation and Cowleaze Chine member, which exhibit two types of failure (Figure 3.14).

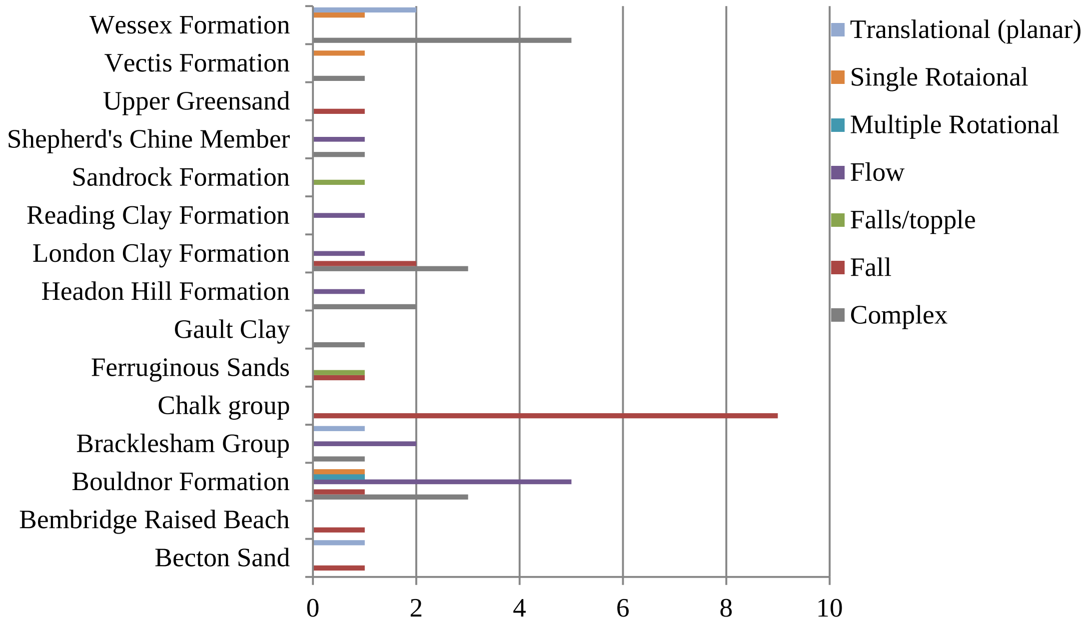


Figure 3.13 The relationship between chronostratigraphy and landslide type for landslides involving a single chronostratigraphic unit.

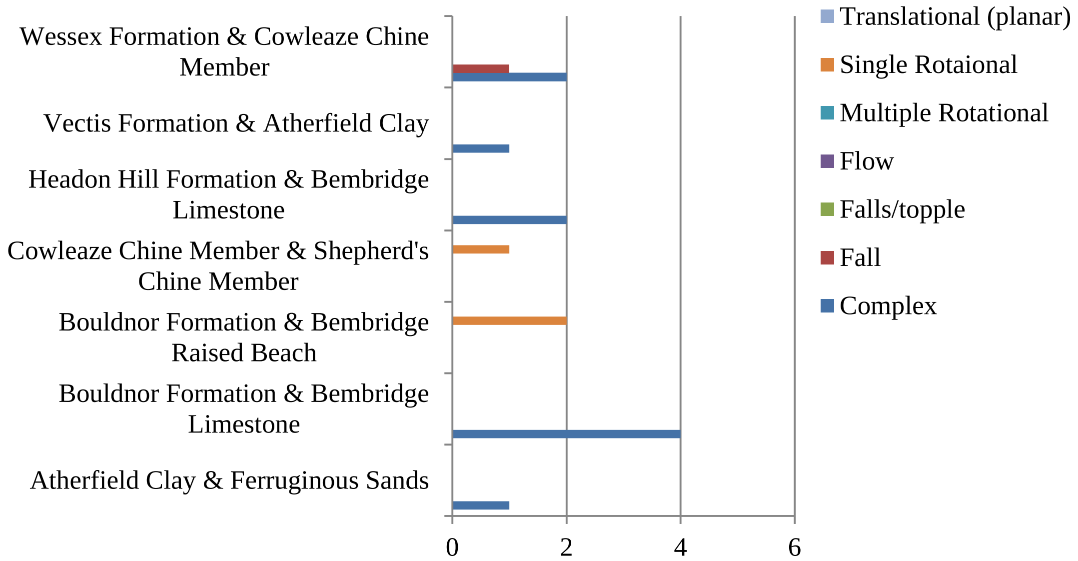


Figure 3.14 The relationship between movement type and chronostratigraphy for landslides involving two chronostratigraphic units.

3.4 Lithology and landslide type

The majority of the lithologies involved with landsliding are of an unlithified nature (Figure 3.11 and 3.12). The majority of these lithologies are arenaceous in nature with the most dominant lithologies involved with landsliding being Silty CLAY, Clayey SILT, Clay and Silt (Figure 3.15-3.17), which generally involve a combination of these different lithologies (Figure 3.16, 3.17). These lithologies most commonly occurred in complex, flow and slide type landslides (Figure 3.15-3.17). The majority of fall type landslide involved lithified material with Chalk being the most common (Figure 3.15-3.17).

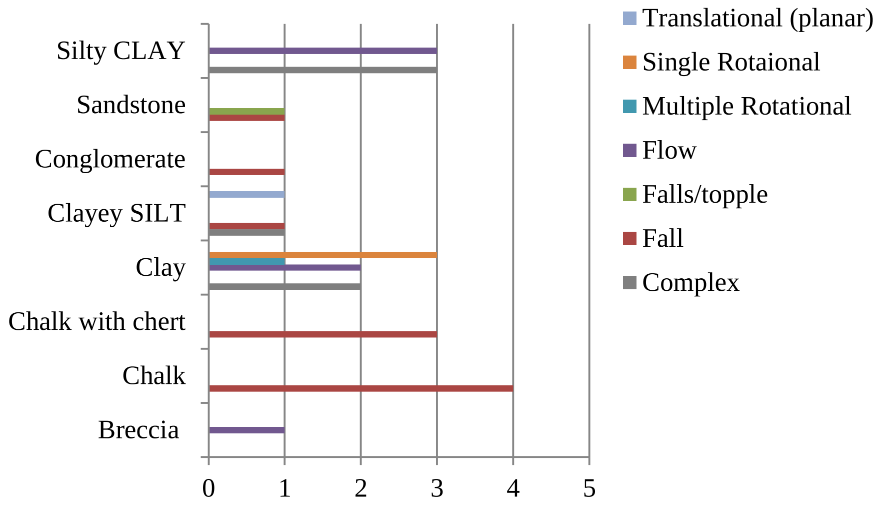


Figure 3.15 The relationship between movement type and lithology for landslides that involved a single lithology.

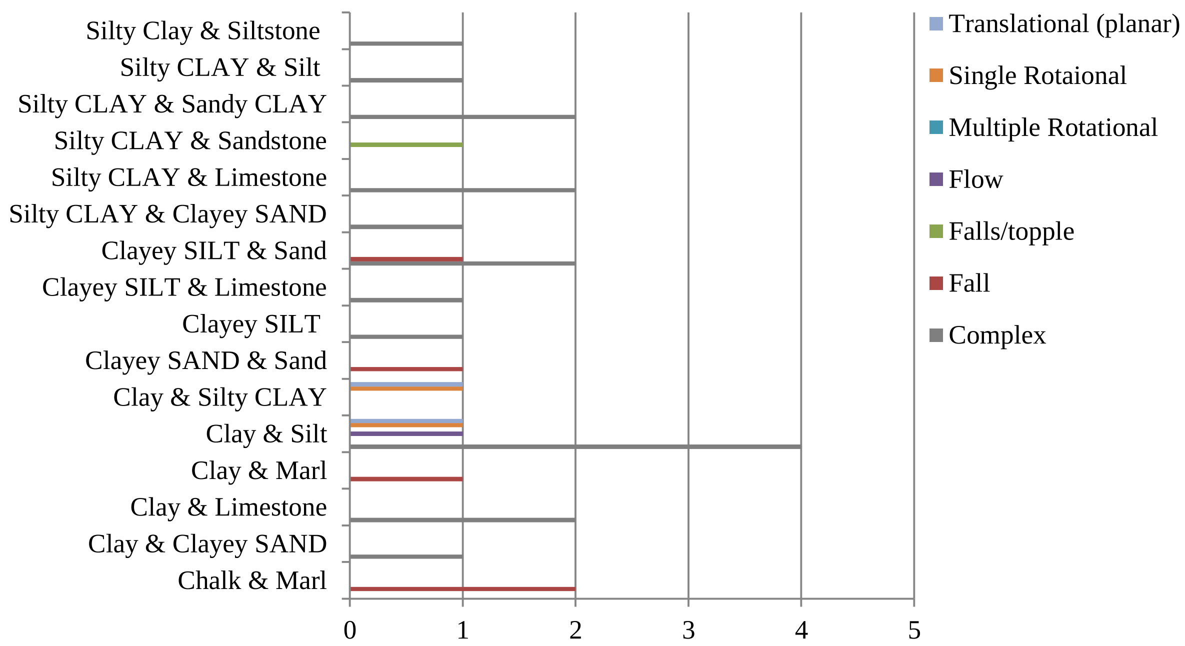


Figure 3.16 The relationship between movement type and lithology for landslides involving two lithologies.

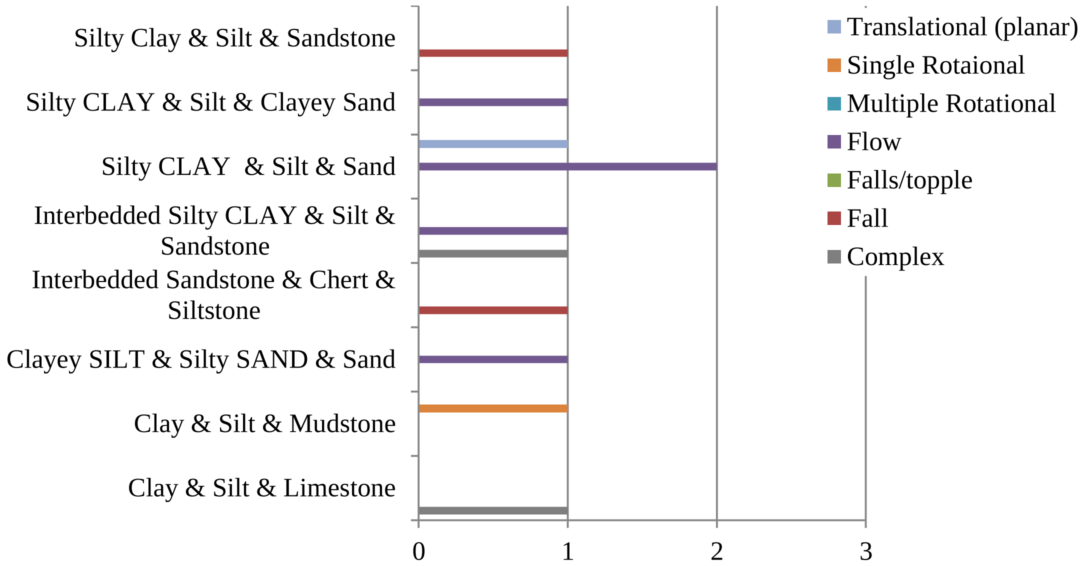


Figure 3.17 The relationship between movement type and lithology for landslides involving three lithologies.

3.5 Lithology and structure of the area

The lithology from Yaverland up to Red Cliff dip shallowly towards the north, with the inversely graded yellow/orange sand with interbedded Silty CLAYs (Barnes High Sandstone) dipping 004/13^o until you reach a succession of sands (Ferruginous Sands) forming a cliff section at Red cliff (Figure 3.10 & 3.11). At this point the dip starts to increase with a dark green Clayey Sand bed in the grey Silty Clay dipping 005/25^o. The lithology then steepens further after the sands until the chalk where it is dipping at nearly 60^o at culver cliff (Figure 3.10 & 3.11). The cliff section from Yaverland to the Chalk cliffs, initially consist of very little sandstones or sands up to red cliff, when a succession of sands then occur. After these sands there are very few lithologies of a Silt or Clay nature and none after the Chalk cliffs are reached (Figure 3.11).

The Chalk at Culver Down (Whitecliff Bay) (Figure 3.12) is steeply dipping towards the north at about 68^o. The lithology after the Chalk cliffs then steepens to near vertical with an ironstone unit dipping at 80^o (Figure 3.12). There is an abrupt change in dip towards the north east of Whitecliff Bay where a succession of limestones change dip over several meters (Figure 3.12). The lithologies after the chalk are mostly Clays, Silts, Clayey SILTs and sands (Figure 3.12). It is at the limestones there is then a change to predominantly clay, silty CLAYs, silts and marls up until Bembridge when there is a conglomerate forming a major part of the cliffs (Figure 3.12).

3.6 Strength properties of the lithologies

Rocks

Table 3.8 Lithologies that gave a Schmidt hammer reading and the compressive strength values using the graph located on the Schmidt hammer.

Lithology	Schmidt hammer reading / R value	Compressive strength / fc psi
15 Coarse yellow sandstone (Figure 3.11)	27.2	2500
26 Pale light brown fine sandstone (Figure 3.11)	32	2800
27 Fine – medium sandstone with chert (Figure 3.11)	31.6	3200
28 Fine green sandstone (Figure 3.11)	26.5	2100
29 Dark green fine sandstone (Figure 3.11)	30.1	2700
30 Blue / grey marl (Figure 3.11)	30	2750
31 Light grey Chalk (Figure 3.11)	30.3	2800
33 White Chalk (Figure 3.11)	31.4	4250
34 White chalk with chert (Figure 3.11)	25.6	1900
39 White very fine Limestone (Figure 3.12)	32.4	5400

Only one of the sand units in the Ferruginous sands at red cliff (Figure 3.10 & 3.11) gave a Schmidt hammer reading. The sandstone units in the Upper Greensand formation near the chalk cliffs (Figure 3.10 & 3.11) all gave Schmidt hammer readings but they all showed relatively low compressive strengths (Table 3.8). The white chalk unit gave the highest compressive strength whilst the lowest compressive strength was given in the white chalk with chert located in Whitecliff bay (Table 3.8). In Whitecliff the only lithology to give a Schmidt hammer reading was a 2.2m thick very fine grained limestone in the Bembridge limestone formation (Figure 3.11 & 3.12) found in the limestone succession that changes dip and gives the greatest compressive strength (Table 3.8).

Soils

Table 3.9 Selected hand penetrometer tests carried out on the cohesive soils of the study area, showing their approximate unconfined strength.

Soil	Weathered state / da N/cm^2	Unweathered state / da N/cm^2
4 Slightly Sandy Clayey SILT (Figure 3.11)	0.67	2.9
3 Clay (Figure 3.11)	2.4	
5 Silty Clay (Figure 3.11)	2.07	1.63
12 silty CLAY (Figure 3.11)	0.6	0.8
14 clayey SAND (Figure 3.11)	2.26	5.1
1 Clay (Figure 3.12)	0.25	0.57
18 clayey SILT Figure (3.12)	1.69	

The penetrometer tests (Table 3.9) show that the cohesive fine soils of the area have very low unconfined strengths and that generally the weathered state of the soils is weaker than the unweathered state.

3.7 Relationship between cliff height and movement type

The majority of Complex landslides in the study area occur in cliff heights between 10 and 40 meters, Fall type landslides occur in a range of cliff heights but the majority are occurring above 40 meter cliff heights (Table 3.10). Flow type landslides are generally occurring in cliff heights from 10 to 40 meters. Slide type landslides occur in cliff heights below 30 meters, with rotational mainly occurring in cliff heights between 10 and 30 meters (Table 3.10).

Table 3.10 The range of cliff heights occurring in the movement types of the study area.

	Average Cliff Height							
Movement Type	0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80
Complex	1 (3.8%)	4 (15.4%)	16 (61.5%)	4 (15.4%)	1 (3.8%)	0	0	0
Fall	0	2 (12.5%)	3 (18.8%)	0	2 (12.5%)	4 (25%)	4 (25%)	1 (6.3%)
Falls/topple	0	0	0	0	2 (100%)	0	0	0
Flow	0	3 (42.9%)	2 (28.6%)	1 (14.3%)	0	1 (14.3%)	0	0
Multiple Rotational	0	0	1 (100%)	0	0	0	0	0
Single Rotational	1 (16.7%)	4 (66.7%)	1 (16.7%)	0	0	0	0	0
Translational (planar)	1 (20%)	1 (20%)	3 (60%)	0	0	0	0	0

For the main movement types occurring in Complex landslides, Flow type are occurring between 10 and 30 meters, rotational between 20-30 meters and Translational (planar) between 10 and 40 meters (Table 3.11).

Table 3.11 The range of cliff heights occurring in the main movement types of Complex landslides.

	Average Cliff Height							
Movement Type	0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80
Flow	0	2 (20%)	8 (80%)	0	0	0	0	0
Multiple Rotational	0	0	0	1 (100%)	0	0	0	0
Single Rotational	1 (16.7%)	0	5 (83.3%)	0	0	0	0	0
Translational (planar)	0	2 (22.2%)	3 (33.3%)	3 (33.3%)	1 (11.1%)	0	0	0

3.8 Relationship between cliff height and offset of rotational slides

There is a positive relationship between cliff height and horizontal displacement with rotational slides (Figure 3.18). The same trend can also be seen for vertical offset (Figure 3.19). The multiple rotational and translational (planar) also generally fit this trend (Figure 3.18 & 3.19). However, the multiple rotational landslide falls the furthest away from the regression line. The regression line for both does not pass through the origin, showing that offset will not occur until about 4/5 meter cliff height (Figure 3.18 & 3.19). The R^2 values show that there is a stronger relationship between cliff height and vertical offset than horizontal offset.

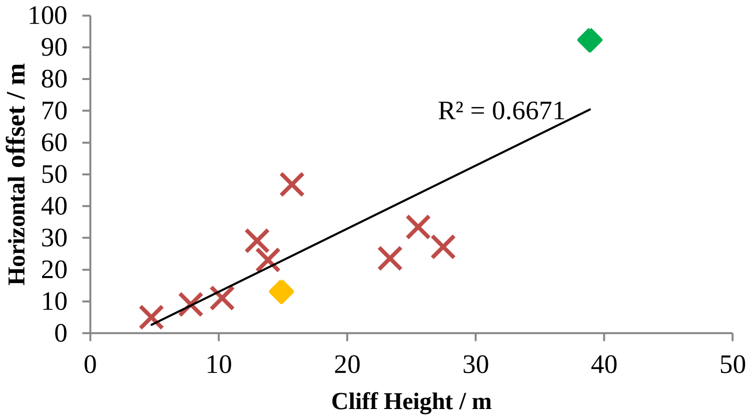


Figure 3.18 The relationship between cliff height and horizontal offset of rotational slides, also showing the front rotational slide of a multiple rotational landslide (green diamond) and a translational (planar) slide (orange diamond). Trend line calculated using linear regression.

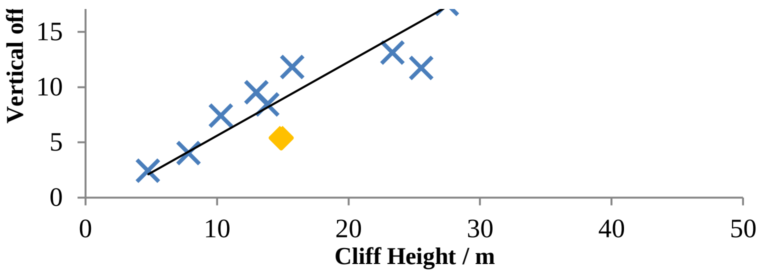


Figure 3.19 The relationship between cliff height and vertical offset of rotational slides, also showing the front rotational slide of a multiple rotational landslide (green diamond) and a translational (planar) slide (orange diamond). Trend line calculated using linear regression.

3.9 Relationship between cliff height and total length of landslide

For both translational (planar) and rotational landslides in the study area, there is a positive relationship between cliff height and total length (Figure 3.20 & 3.21). There is some variation in the data as a complex (translational (planar)) and translational (planar) landslide lie far from the regression line (Figure 3.20). Similarly the multiple rotational landslides lie the furthest away from the regression line (Figure 3.21). The R^2

values for both relationships are similar and relatively high showing there is a relatively strong positive relationship between the data.

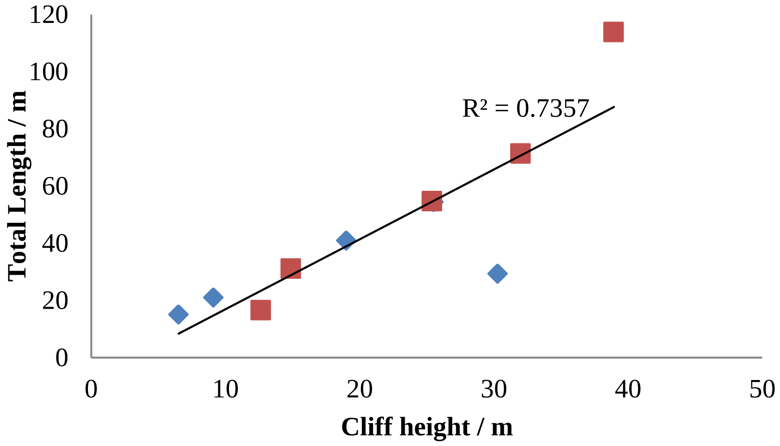


Figure 3.20 The relationship between cliff height and total length of landslides with translational (planar) nature. Red squares: Complex landslides with main movement being Translational (planar). Blue diamonds: Translational (planar) landslides. Trend line calculated using linear regression.

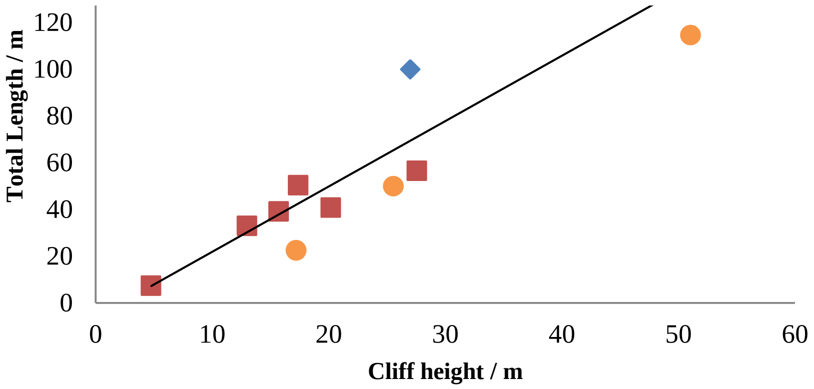


Figure 3.21 The relationship between cliff height and total length of landslides with rotational nature. Red squares: Single rotational, blue diamonds: Multiple rotational, orange circles: Complex (Single rotational), circle with the greatest height is Complex (multiple rotational). Trend line calculated using linear regression.

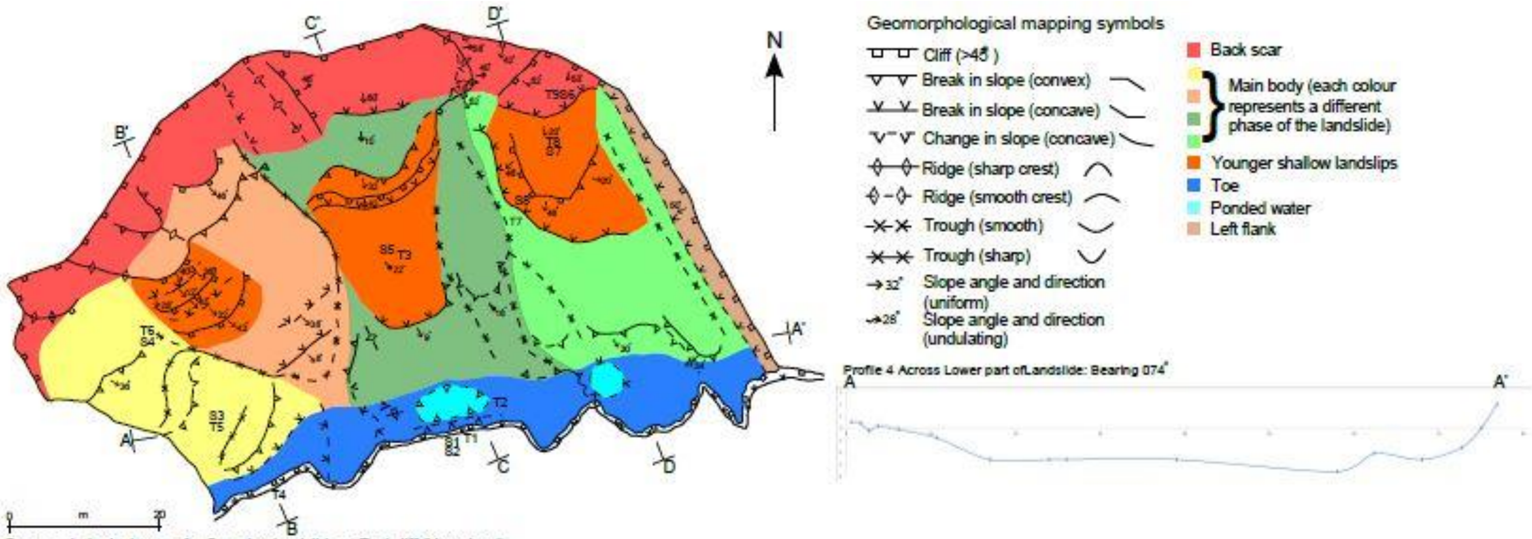
3.10 Mapped Complex landslide at Red cliff (Sandown Bay, north) (Figure 3.22)

The landslide is about 100m at its widest extent by about 50 m at its greatest extent from the back scar to the toe of the landslide (total length). It is complex in nature with it appearing to consist of a series of failures. It has a clear back scar, body, toe area and left flank with a series of younger failures occurring in the body area. The back scar has steep slopes at about 50^{o} with the gradient decreasing towards the toe but it is highly variable.

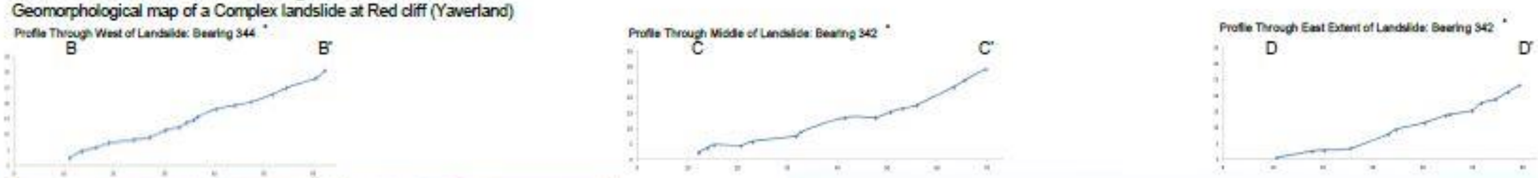
The shear vein tests show that the undrained shear strength is generally low for the central main body area of the landslide, whilst the T1 taken from the front of the rotated block and T9 taken from the back scar of the landslide show the highest undrained shear strength (Table 3.12). T7, which was taken from the front of a younger shallower rotated block, is an exception as it has a higher undrained shear strength than all the samples apart from T1 and T9.

Table 3.12 Field shear vein test conducted on the soils in the field from which samples were taken from, showing in situ undrained shear strength. Numbers correspond to the location the tests were carried out on the landslide e.g. 1 = T1 on landslide (Figure 3.21). Apart from T3 the other tests were carried out where the samples were collected from (see, figure 3.21).

Test	Shear Vein Test (19 mm Vein at depth 20-24cm) / KPa
1	52.6
2	22.8
3	22
4	16.8
5	17.6
6	12.6
7	47.2
8	26.4
9	54



Geomorphological map of a Complex landslide at Red cliff (Yaverland)



Google Earth imagery showing how the landslide has evolved with age. Landslide is outlined in red.

Image 1 displaying the extent of the lanslide, person circled for scale. Areas identified with dashed lines correspond to images below.

Image 2 (right) displaying a recent shallow slip. Area identified by yellow dotted line on image above.

Images 3 & 4 (above) showing tension cracks (left) of a recent shallow slide (right). Area idicated by Aqua dotted line on image above.

Image 5 (above) showing what appears to be the slip surface of a more recent landslip on the larger landslide.

Figure 3.22 Data compiled for Complex landslide located at Red cliff (Sandown Bay, north)); geomorphological map (top left), profiles (middle), google earth imagery (bottom left) and images of the landslide and areas of interest (bottom right).

The plastic limits of the samples taken from the landslides are similar except for samples 3 and 4 which have a slightly higher and much higher plastic limit respectively than the other soils (Table 3.13). The liquid limits and plasticity index of the samples are much more variable. The liquidity index for the majority of the samples are close to zero except for sample 5 which is closer to one and sample 1 is the farthest away from zero in terms of its negative value (Table 3.13).

Table 3.13 Atterberg limits conducted on the soil samples taken from the landslides. The numbers correspond to the location on the landslide in which the samples were taken from.

Sample	Plastic Limit	Liquid Limit	Plasticity Index	Liquidity Index
1 Slightly Clayey Sandy SILT	19.84	30.07	10.23	-0.29
2 Slightly Sandy CLAY	19.74	45.12	25.38	0.18
3 Silty CLAY with rare rootlets	25.11	70.84	45.74	0.12
4 Slightly Sandy Silty CLAY	35.05	59.50	24.45	-0.01
5 Slightly Silty Sandy CLAY	19.31	40.58	21.27	0.54
6 Silty CLAY	21.85	55.42	33.58	0.17
7 Slightly Silty Sandy CLAY	19.98	37.90	17.92	0.18
8 Slightly Sandy CLAY	17.84	38.03	20.18	0.09

All the profiles that pass from the front to the back of the landslide have a convex section at the bottom of the profile. Profiles 1 and 2 are overall slightly concave than but profile 3 is generally straight. All the profiles have a central convex part which is more pronounced in profile 2. The top parts of the profiles are generally straight but they all have a slight convex part after the central convex section which is more pronounced in profile 1. All the major parts of the profiles identified also occur around the same horizontal distances. The profile (4) that was taken across the bottom of the landslide shows that away from the sides of the landslide it gets deeper towards the middle. The west side of the profile is generally convex whilst the east side of the profile is concave and is also steeper than the west side. The east side of the profile also has a convex part immediately left of the concave side.

The plasticity chart (Figure 3.23) shows the soils have a wide range of plasticity from low to very high and all but one of the samples plot above the A line. It also shows that samples can generally be classified as Clays with the exception of sample 4.

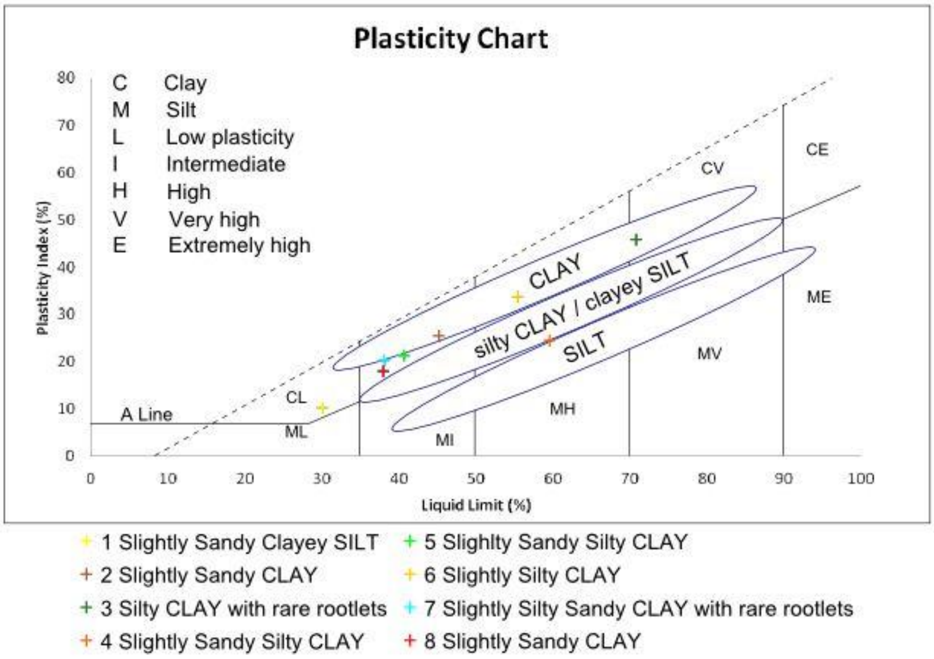


Figure 3.23 Plasticity chart after Figure 4.17 Norbury (2010).

The moisture content for all the samples varies (Table 3.14). The angle of internal friction for each soil varies but soils 1 and 2 have much higher angle of internal friction than the rest of the soils. The coefficient of cohesion also varies greatly for each sample (Table 3.14).

Table 3.14 Direct shear box tests completed on undrained soil samples. The numbers respond to the location the soils samples were taken from.

Sample	Moisture Content / %	Angle of internal friction	Coefficient of Cohesion
1 Slightly Clayey Sandy SILT	16.91	38.98	5.67
2 Slightly Sandy CLAY	24.23	33.53	8.89
3 Silty CLAY with rare rootlets	30.61	14.47	33.74
4 Slightly Sandy Silty CLAY	34.73	7.09	11.72
5 Slightly Silty Sandy CLAY	30.73	4.79	9.09
6 Silty CLAY	27.45	19.71	26.60
7 Slightly Silty Sandy CLAY	23.12	7.96	16.77
8 Slightly Sandy CLAY	19.72	19.95	28.00

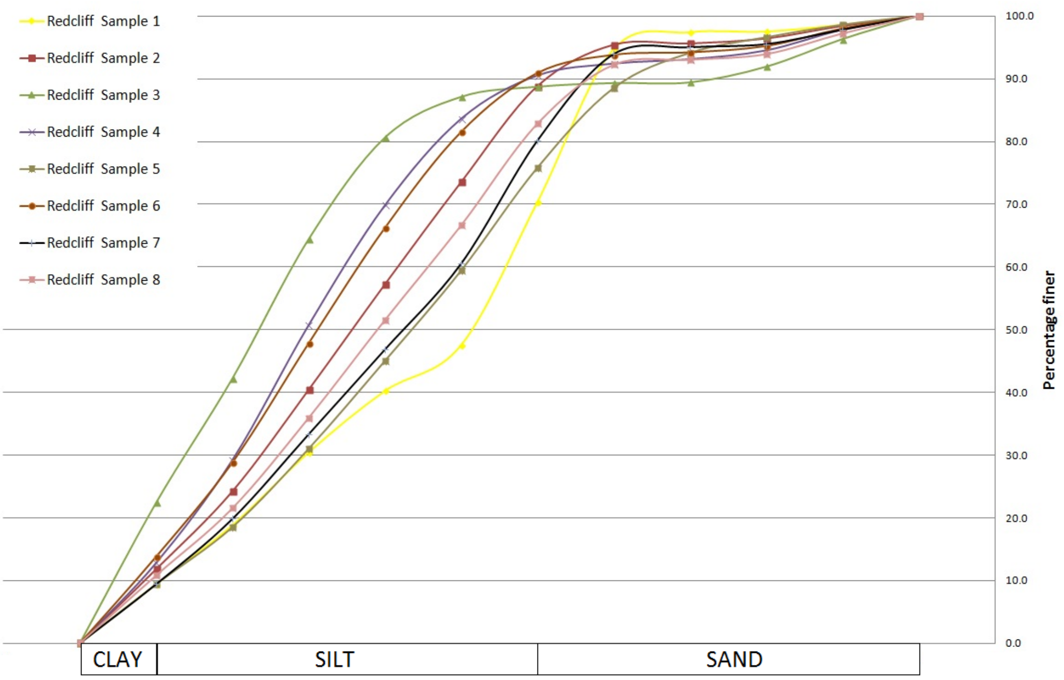


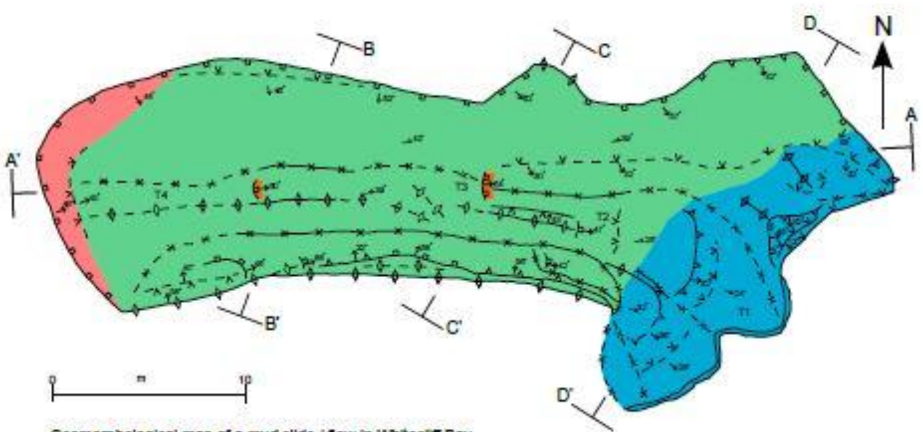
Figure 3.24 Particle size distribution plot (see appendix D for percentage break down) for the samples taken from the Complex landslide at Red cliff (Sandown Bay). Numbers correspond to locations samples were taken (see geomorphological map Figure).

The particle size distribution plots (Figure 3.24) show that sample 3 has the highest proportion of clay sized particles whilst the other samples have similar clay percentages. Samples 1, 5, 7 and 8 have higher proportions of sand sized particles than the other samples and the samples as a whole have varying percentages of silt sized particles.

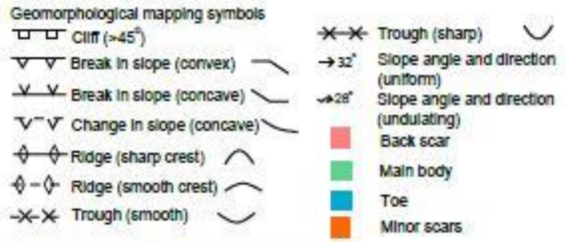
3.11 Mapped mud slide / flow landslide in Whitecliff Bay (Figure 3.25)

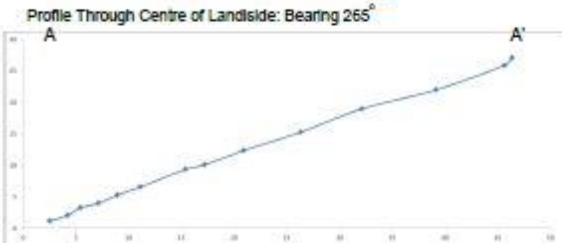
The landslide has a distinct elongate form and spreads out at the toe area. It also has some minor scars occurring in the main body of the landslide. The total length of the landslide is about 44m but is only about 11m at its widest extent.

The profiles taken across the landslide show, it is wider at the back and the front than in the middle of the landslide. The cross profiles also show that the landslide gets deeper from the front to the back of the landslide. The profile showing the extent of the landslide from back to front shows that it is generally straight with slight undulation.

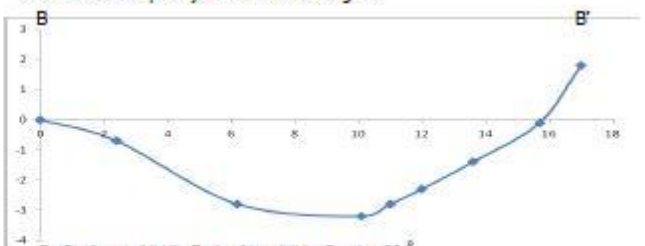


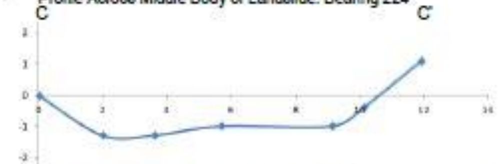
Geomorphological map of a mud slide / flow in Whitecliff Bay.

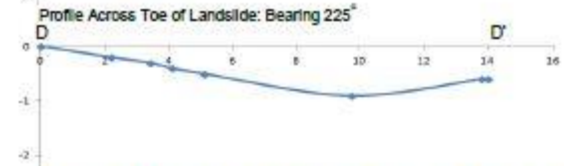




Profile taken up through the landslide, showing the variation of the surface.







Profiles taken across the landslide show how the surface of the landslide varies laterally.

Image 1 displaying the extent of the mapped landslide.

Image 2displaying the bowl / channel shape of the back of the landslide.

Image 3 showing other possibile similar type landslides occurring in close proximity.

Image 4 showing a thin limestone exposed on the north side of the landslide; blocks of the landslide re-appear on the north slopes of the landslide with various displacements.

Figure 3.25 Data compiled for a mud slide / flow occurring in Whitecliff Bay; geomorphological map (top left), profiles (top right & below geomorphological map) and images (bottom right).

Table 3.15 Direct shear box tests completed on undrained soil samples. The numbers respond to the location the soils samples were taken from.

Sample	Moisture Content	Angle of internal friction	Coefficient of Cohesion
1 Silty Sandy CLAY	23.86	27.15	30.75
2 Slightly Sandy CLAY with frequent shell fragments	25.16	13.26	43.09
3 Slightly Sandy CLAY with rare shell fragments	30.15	20.37	19.50
4 Slightly Silty CLAY	26.21	8.28	26.44

The shear box test results (Table 3.15), show that the angle of internal friction and coefficient of cohesion vary for each sample but the moisture contents are much less variable.

Table 3.16 Field shear vein tests conducted in the field from which the samples were taken, showing their undrained shear strength. Numbers correspond to the location the tests were carried out on the landslide e.g. 1 = T1 on landslide (Figure 3.24).

Test	Shear Vein Test (19mm Vein at depth 32cm) / KPa
1	43.6
2	107.8
3	67.4
4	86.8

The shear vein results generally show that shear strength increases towards the back of the landslide except for test 2 which has the highest shear strength (Table 3.16).

Table 3.17 Atterberg limits conducted on the soil samples taken from the landslides. The numbers correspond to the location on the landslide in which the samples were taken from.

Sample	Plastic Limit	Liquid Limit	Plasticity Index	Liquidity Index
1 Silty Sandy CLAY	25.60	47.07	21.47	-0.08
2 Slightly Sandy CLAY with frequent shell fragments	24.73	55.47	30.73	0.01
3 Slightly Sandy CLAY with rare shell fragments	25.48	55.31	29.83	0.16
4 Slightly Silty CLAY	24.89	49.93	25.05	0.05

The plastic limits do not vary greatly between the samples but the liquid limits are slightly more variable with samples 1 and 4 having similar liquid limits but are lower than samples 2 and 3 which have similar liquid limits (Table 3.17). The plasticity index follows the same pattern except samples 1 and 4 show a slightly larger difference. The liquidity index for all the samples are close to zero.

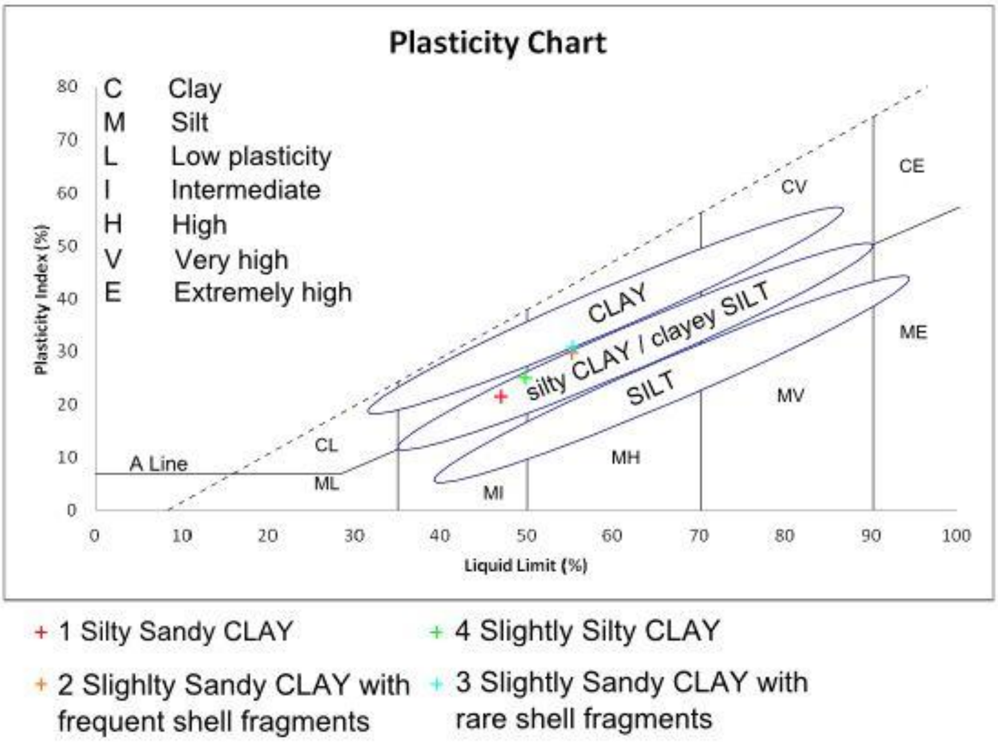


Figure 3.26 Plasticity chart after Figure 4.17 Norbury (2010).

The plasticity chart (Figure 3.26) shows that the samples plot in close proximity and that the plasticity of the samples ranges from intermediate to high. All the samples plot above the A line and can be classed as silty CLAYs or CLAYs.

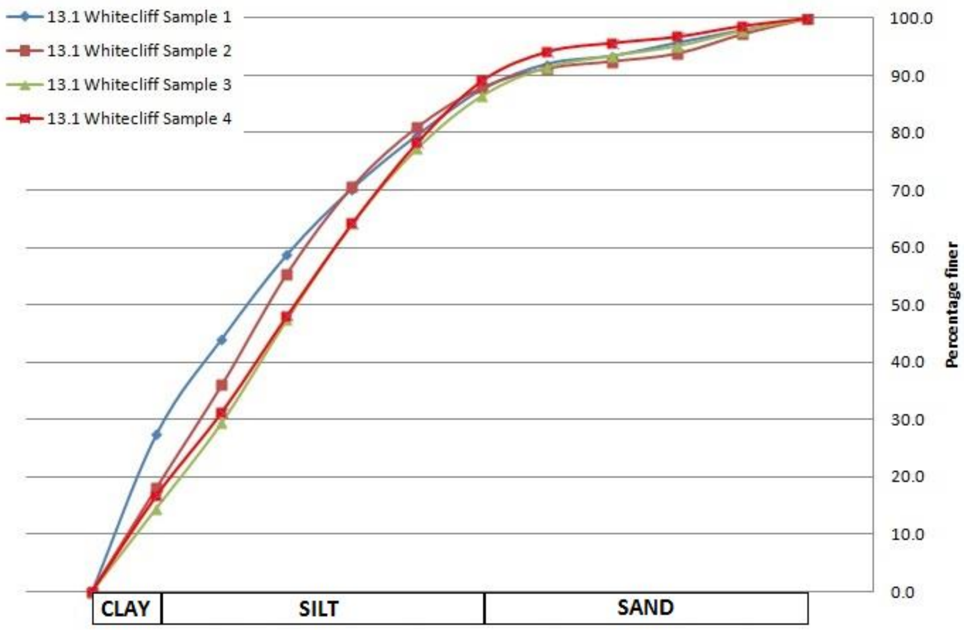


Figure 3.27 Particle size distribution plot (see appendix D for percentage break down) for the samples taken from the mud slide / flow landslide at Whitecliff. Numbers correspond to locations samples were taken (see geomorphological map Figure).

The particle size distribution plots show that the samples have similar percentages Sand and Silt or finer particles but sample 1 has the highest percentage of clay sized particles. The other three samples have similar percentages of clay sized particles (Figure 3.27).

Chapter four: Discussion

4.1 Factors preparing conditions for landsliding in the area

Geology and lithology

The results show that bedrock geology is exerting a strong influence on landsliding in the area as very few landslides involved a superficial geology (Table 3.5). This then implies that failure is principally occurring in the bedrock geology. However, only one, well developed, superficial geology was found in the study area, occurring in Yaverland (Figure 3.11) but nearly every time it was found in the displaced mass of a landslide, the bedrock geology was found failed too, supporting the fact that failure most likely occurred in the bedrock geology causing the superficial geology to fail as well. The geology and thus lithology forming the south east of the Isle of Wight is a major factor in why the area is highly susceptible to landsliding. The lithology generally consists of weak, soft, poorly lithified sedimentary rocks (Figure 3.11 & 3.12) with some stronger rock outcrops, mainly at Culver cliff. The weakness of the lithology is highlighted in the Schmidt hammer tests, with only a few lithologies out of the entire area giving a Schmidt hammer reading showing, that for the majority of the lithologies in the area, the impact of the Schmidt hammer is greater than the lithology it is impacting on (Day, 1980), thus showing its inherent weakness. The lithologies that gave a Schmidt hammer reading (Table 3.8, Figure 3.11 & 3.12) were all generally low and are classified by (Selby, 1980) as very weak rock. Thus, with the rocks being inherently weak it shows that, where they form slopes, they will not be able to withstand great stresses and therefore are highly susceptible to landsliding. The penetrometer readings (Table 3.9) highlight how weak the soil lithologies are in the area, as Barnes, (2010) states the shear strength of the material will be about half their unconfined strength and thus explains why these soils are so prone to landsliding (Figure 3.11 & 3.12) Even though all the lithologies are weak in terms of their strength, there are some that are offering more resistance to landsliding. At red cliff, little landsliding is occurring in the Ferruginous sands at red cliff (Figure 3.10 & 3.11); with only a recent Fall (19; Figure 3.11) occurring in the sands and the Fall / Topple zones being dormant (20/21; Figure 3.11). This relative inactivity of landsliding in these sands is most likely due to the strength of the material. The rate at which the cliff line has retreated is a good indicator of the material, which is forming the cliff, resistance to erosion. The Ferruginous sands at Red cliff (Figure 4.1) have not retreated as much as the cliff sections either side of it, showing that it must be more resistant to erosion and thus inherently stronger than the lithologies either side of the succession. This is the case as the lithologies either side of it are of a clay nature (Figure 3.11) and clay is consistently seen as the weakest material (Foster, 2007). The chalk cliffs show even less recession showing that the chalk group are more resistant to erosion than the Ferruginous sands and this is supported by the Schmidt hammer readings (Table 6). This relationship with lithology and cliff line retreat is also highlighted by May (1980) along the south west coast of the isle of Wight. The cliff heights also increase at the sands and the chalk which is argued by Jenkins et al. (2011) shows the stratas resistant to coastal erosion which is related to the strength of the lithology forming the cliffs.

Figure 4.1 Google Earth imagery showing the outline of the cliffs at Red cliff and Culver Down. Cliff outline is highlighted by red dotted line. Yellow bar shows the location of the succession of sands (Ferruginous sands) involving the lithologies 15 – 19 (Figure 3.11). Lime bar shows the location of the chalk cliffs (Chalk group) involving the lithologies 30 – 34 (Figure 13.1).

The resistance that different lithologies are having to landsliding is also highlighted in Whitecliff where the pattern of landsliding is occurring in the clays and silts and the less slipped areas in sands (Figure 3.12 & 4.2). This then shows that the clayey and silty lithologies are more susceptible to landsliding than the sands and thus must be inherently weaker. The left landslide failure is shallower than the right (Figure 4.2) which could also be due to the fact the lithology involved in the landslide has more sand, showing that more homogenous clayey/silty units are prone to more, well developed (deeper) landsliding. The weakness of the clay lithologies to erosion and thus susceptibility to landsliding is highlighted by gullies forming in Silty SAND units where there is a more prominent clay horizon occurring (Figure 4.3). Thus further showing where clay is occurring or forms a fraction of a lithology then it will be more prone to landsliding and this is what is being seen in the study area (Figure 3.11, 3.12 & 3.15-3.17). This is supported by the fact that Jones and Lee (1994) state that as the clay content increases, a material becomes weaker and thus more prone to failure.

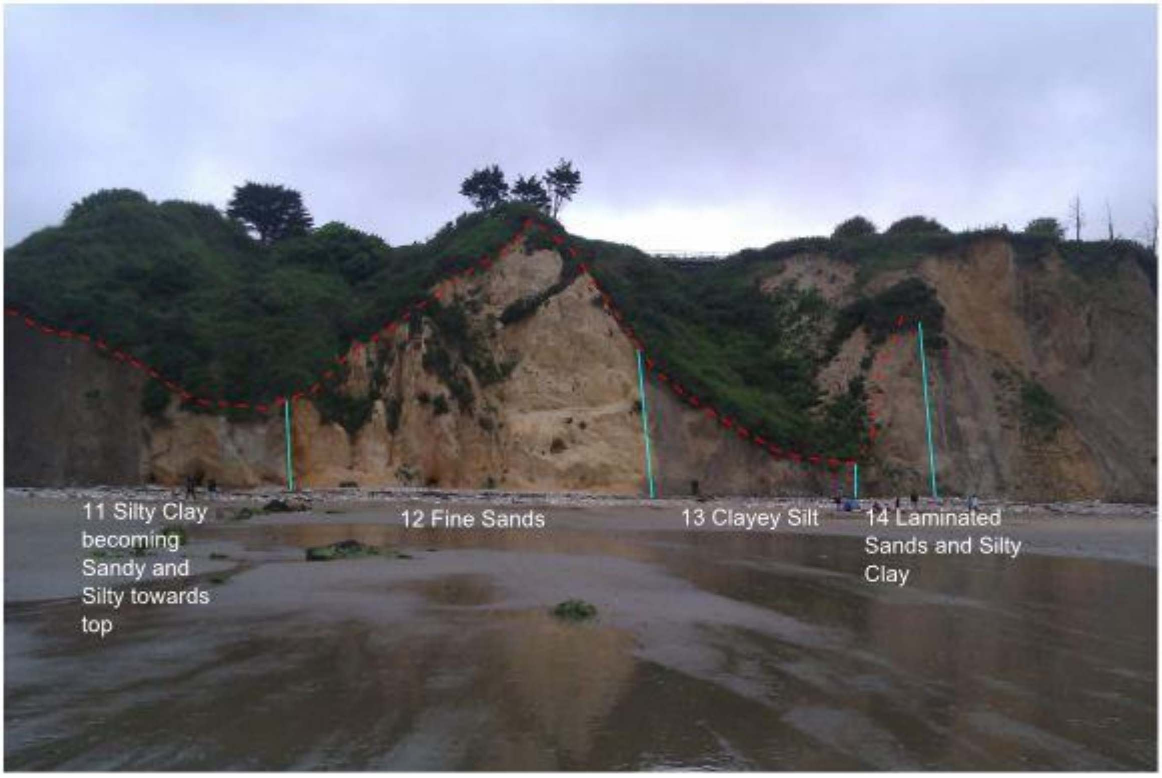


Figure 4.2 An example of landslide occurrence related to lithology type. Red dashed line indicate the outline of the failures and blue / aqua lines indicate the boundaries between the

Figure 4.3 Gullies forming where there is a thicker clay horizon, located left of the red dotted line.

Discontinuities

Discontinuities such as bedding surfaces, faults and joints can weaken a soil or rock mass (Cruden and Varnes, 1998). Bedding surfaces are prominent in the study area due to the nature and continual change of the lithology along the cliff sections (Figure 3.11 & 3.12) and thus is most likely contributing to the susceptibility of the cliff sections to landsliding. However, the lithology in the study area is dipping towards the north and into the slope which would produce little instability of the slope (Emery and Khun, 1982). However, landslides 11, 14, 15, 16 and 17 (Figure 3.12) are all occurring where bedding surfaces (contacts) occur and thus they could be making the slopes more susceptible to landsliding. Landslide 9 (Figure 3.12 & 4.4) shows that the deepest part of the landslide is in the centre implying that the failure occurred towards the centre of the landslide and thus away from the bedding surfaces, showing that they may have had little influence on this landslide.

Figure 4.4 Complex landslide (9, Figure 3.12) showing the relationship between bedding surfaces and the extent of the landslide.

The effect that discontinuities can have on the susceptibility of a lithology to landsliding is highlighted by the chalk forming the cliffs at Culver cliff. Apart from the Limestone in Whitecliff the Chalk is the strongest material in the study area (Table 3.8) but rock falls are dominantly occurring along the cliffs (Figure 3.12). This is most likely due to the well developed discontinuities that run almost perpendicular to the bedding (Figure 4.5). Discontinuities influence the stability of a rock slope (Piteau and Peckover, 1978), acting as possible planes of failure (Foster, 2007), thus these discontinuities will then allow the chalk to detach with little or no shear which normally occurs with fall type landslides (Cruden and Varnes, 1996). It is then due to these discontinuities that the cliffs consisting of chalk and marl are highly susceptible to Fall type landslides and highlights how they can weaken a material.

Figure 4.5 Discontinuities developed in the interbedded chalk and marls at Culver cliff. Notice that the discontinuities are running at nearly right angles to the bedding. This was also seen in the whiter Chalk succession seen after this.

Rainfall

There was numerous evidence of the influence that rainfall might be having on landsliding in the area; water was seen to be flowing out of the back scar area of a single rotational slide in Whitecliff (36, Figure 3.12) whilst an earth flow consisting of clay (which was at or close to its liquid limit) was actively moving on 12th June 2012. This was preceded by near continuous rainfall amounting to 364mm falling in the space of 10 days (Isle of Wight weather, 2013a; 2013b, see Appendix A & B) and thus is the most likely cause for the flow to be actively moving. As rainwater increasingly infiltrates the ground it causes the pressure of the water that fills the voids between soil particles to increase, which in turn causes a decrease in effective stress, leading to the slope becoming more unstable (Matsuura et al. 2008). This then could have triggered the single rotational landslide in Whitecliff, especially if the aquifer reached a more impermeable layer, which is highly likely due to the lithology consisting of clay, silt and marls. The pore water pressures would have increased against the impermeable layer and locally could have caused a curved shear surface to form, triggering a rotational slide. The most common type of weather-induced landslides are flow and slide types (Cruden and Varnes, 1996) and as the majority of the landslides in the area are of flow and slide type there is then a strong relationship that rainfall is a prime cause for landsliding in the area.

Due to the dominance of low permeable fine soils forming a major component of the lithology in the area (figure 3.11 & 3.12), there is then the potential for shear surfaces to develop where there is a contact between a more permeable layer such as a sand and a more impermeable layer such as a clay. The water meeting the more impermeable layer will cause an increase in pore water pressures and this increase can reach a point when it overcomes the shear strength of the material forming the slope thus producing a shear surface for failure to occur on (Jones and Lee, 1994). However, where the bedding contacts are vertical (Whitecliff, Figure 3.12) it is unlikely that significant pore water pressures will develop as the water will be able to flow parallel to the bedding, under the influence of gravity, as the dip of the bedding favours the ingress of water (Jones and Lee, 1994). This is supported by the fact that slip surfaces along bedding contacts between low and high permeable layers do not appear to be occurring in Whitecliff (Figure 3.12, 24 & 26). However, it could be a possible mechanism for landsliding in parts of Yaverland (Figure 4.6) as the lithology is dipping shallowly not steeply. The failure has mainly occurred in the Silty SAND unit running along the top of the cliff. The unit below this is a more impermeable Silty CLAY and thus during high rainfall, pore water pressures could have built up along this impermeable layer until it caused the unit above to fail.

Figure 4.6 Failure occurring in the superficial geology, which is possibly related to increased pore pressures at impermeable layers.

Rainfall also causes an increase in the soils moisture content, decreasing matric suction and thus reducing the shear strength of the soil (Kim et al. 2012) making the soil more susceptible to failure. The rate at which the moisture content of a soil will increase will depend on the permeability of the soil and due to the majority of the area consisting of fine soils (low permeability), it will take a longer response for the mass of material to fail. However, with increasing moisture content in impermeable fine soils, it will take longer for the water to dissipate. Thus, if there are continuous amounts of rainfall it might eventually lead to failures occurring in the low permeable soils but none occurring in more permeable soils as they can remove their water content quicker. The other effect of rainfall is that it causes an increase in the moisture content of a mass material which will increase its weight and thus will increase the stress along a failure plane which can trigger a failure (Young and Ashford, 2008). This will also have the effect of increasing the load on a slope, thus increasing stress which can overcome the strength of the material forming the slope initiating failure.

Marine processes

At high tide the sea reaches the base of the cliffs in most of the area (Figure 4.7) except in parts of Yaverland especially from the succession of sands (Ferruginous Sands) up until the chalk. The effect that the sea will have will be to remove material from the toe of a landslide. This then reduces the stability of the slope and can promote further recession through landsliding (Lee et al. 2001). The removal of material from the base of a slope also causes the slope to steepen which is argued by Wolters and Muller (2008) as being the critical factor for increasing slope instability. However, the deposition of material at that base of the slope provides protection from wave run-up and thus erosion only occurs when the debris has been removed (Lee, 2008). This then could also explain why the chalk group has receded the least, as the falls will deposit material at the base of the slope providing a natural protection to marine erosion. This effect will be diminished in soft rock cliffs (majority of the study area) as the displaced material deposited at the base of the cliff / slope will be highly disturbed and in a fully softened state which will mean it can be easily eroded (Castedo et al. 2012).Thus, this will have the effect to provide the condition for continuous landsliding as marine processes will be able to easily remove material from the base of slopes as most of the area consists of soft rock cliffs (Figure 3.11 & 3.12).

Figure 4.7 Evidence of the sea reaching the base of the cliffs near high tide.

The problem with the effects of marine erosion is that it can promote new failures to occur on previously stable slopes but also has the effect of promoting continuous landsliding in already landslide prone area and this explains why the majority of the area is landsliding. It is also stated by Young and Ashford (2008) that the periodic loading of the foreshore during the tidal cycle can cause a rock mass, such as the chalk forming the cliffs at Culver, to undergo periodic flexure which will exert its own stress on the rock mass. This then could have the effect of initiating the falls seen in the chalk at Culver cliff.

Even though the sea does not reach the base of the cliff at the Ferruginous Sands (Figure 3.9), there is still evidence of marine processes affecting the sands in the form of tafoni (Figure 4.8). The tafoni is most likely due to salt weathering (Huinink et al. 2004), due to it being a coastal setting, and is an example of cavernous weathering and results in the weakening of the cliff face (Mol and Viles, 2012). Thus, this can lead to the development of material falling from the cliff face and as tafoin structures can grow in size and coalesce to from larger forms (Sunamura and Aoki, 2011), this then could allow material to detach without shearing to produce falls.

Figure 4.8 Tafoni forming in the sand cliffs of the Ferruginous sands in Sandown Bay.

4.3 Geological and lithological control on landslide type

Lithology is a major factor for the area being extremely prone to landsliding but the nature and type of the lithology is also influencing the type of movement that occurs in the landslide. Fine soils with varying amounts of clay and silt compositions are dominantly producing complex, flow and slide type landslides (Figure 3.15 – 3.17). Comparing this to data compiled by the Government department of the Environment (Table 5.2 (Jones and Lee, 1994), it is similarly seen that the majority of landslides with a clay lithology are producing complex landslides. However, their data show single rotational being the next most dominant associated with clay, but this is not being seen in the study area, which is most likely due to the fact that the soils are not purely of a clay composition. Fall type landslides are dominantly occurring in Chalk (Figure 3.15-3.17) and this is similarly seen for the data produced by the Government department of the Environment (Table 5.2, (Jones and Lee, 1994) showing that this lithology is having a strong control on the landslide type where it occurs.

Both areas have similar lithologies in terms of the poorly lithified material but Flow type landslides are more dominant in Whitecliff, whereas rotational landslides are more dominant in Sandown Bay (including the main movement types in Complex landslides for both areas) (Table 3.1 & 3.2). This difference in the two areas is most likely due to the differences in the dip of the lithology. The silt and clay lithologies that are occurring in Sandown Bay are shallowly dipping (Figure 3.11) but in Whitecliff Bay the lithology are dipping near vertical (Figure 3.12). This then shows that when the lithology is dipping shallowly (13^o) a surface of rupture is most likely to develop that is curved but when the lithology is steeply dipping (80^o) then a surface of rupture is less likely to occur (Cruden and Varnes, 1996). However, in the north part of Whitecliff where the dip is shallow there are no rotational landslides occurring where the limestone succession exists in the cliff (lithology 39 Figure 3.12). This is most likely due to the limestone reinforcing the cliff and preventing a rupture surface from developing thus causing the landsliding to occur as flows. This is also seen along the section of coastline at Hamstead; where a limestone outcropping on the beach (same as the one in Whitecliff) is influencing the rate of recession and activity of landsliding above it (Hutchinson, 1983). The influence that this limestone is having on the type of movement produced in a landslide is amplified when the limestone disappears under the beach (Figure 3.12); rotational landslides then start to dominate (Figure 3.12) which further suggesting that when the slope predominantly consists of clayey or silty materials and the lithology is dipping gently, then a curved rupture surface is most likely to occur. This also highlights that not only does the lithology influence the distribution and type of movement in a landslide but also the structural nature of the lithology. The relationship between the dip of the lithology and the type of landslides occurring is the result of the structural geology of the area and the change in the dip of the beds is due to the Isle of Wight Monocline (Insole et al. 1998; Hopson, 2011) and shows the control that the geological history can have on the type and occurrence of landsliding in the area.

4.4 Physical properties of materials forming the slopes

The physical properties of the materials occurring in the Complex landslide at red cliff (Figure 3.22) are highly variable across the whole of the landslide (Table 3.13) but some relationships can be drawn. Plasticity is the property of a clay material which allows it to deform permanently under stress without rupturing, up to an elastic yield point (Reeves et al. 2006) and will retain its shape once the force is removed (Andrade et al. 2011). Thus, a clayey soil with high plasticity can undergo a greater stress without rupturing than a clayey soil with low plasticity. Most of the samples have a lower plasticity than sample 6 which was taken from the back scar of the landslide and thus the difference in the plasticity could then have caused the landslide. However, due to the samples being taken from the same landslide the lithology for all the samples should be the same and thus should have similar physical properties but this is not being seen. This is most likely due to the material being mixed and deformed due to failure and thus the test results highlight how the physical properties have changed compared to its original state which is shown by sample 6. The undrained shear strength of the samples taken from the toe and main body area of the landslide are weaker than the back scar, showing that after failure occurs the material becomes weaker. This has major implications as the failed material will now be more susceptible to landsliding and this is being shown by the series of younger failures highlighted on the geomorphological map.

The results of the atterberg limits and particle size distribution show similar physical properties to that of the samples of Muggaga et al. (2012) in their study. They indicate that their samples have high expansive potential and thus as some of the samples in this study show similar physical properties the materials in both landslide (Figure 3.22 & 3.25) are also likely to have high expansive potential making them highly susceptible to landsliding (Muggaga et al. 2012), thus, explaining why landsliding has occurred. Due to the variation in the physical properties of the samples (Table 3.13 & 3.17) the samples will swell at different moisture contents and thus stress will be exerted on the slopes at different times depending on the physical properties of the material and this could explain why the landslide in red cliff is seen to progressively fail and not fail at the same time (Figure 3.22).

The undrained shear strength of test 3 (Table 3.12) which was taken in a younger failure is very low and could explain why the material has failed and tension cracks are forming a small shallow failures are occurring (Figure 3.22, image 3 & 4). The liquidity index of sample 5 from which T3 was carried out, indicates it was approaching its liquid limit (Selby, 1993) (Table 3.13). The moisture contents of the samples don't show a relationship with the undrained shear strength of the materials, which is unusual as an increase in water content would weaken a material. However, Andrade et al. (2011) states that an initial increase in water content increases cohesion and increases the shear resistance of the material until it generally passes its plastic limit. As the plastic limits of the samples vary, each samples' shearing resistance would vary with different moisture contents and thus this could explain why there appears to be no relationship. T6, which involved sample 4, shows the lowest undrained shear strength out of all the materials in its natural state but the liquidity index implies that it is in a solid state. It was noticed in the field that the material was almost completely saturated and thus must have been close to its liquid limit. This could then be an anomalous result and the natural moisture content could have been lost by the sample not being properly sealed. However, its low undrained shear strength at the time of the test does explain why there has been a recent shallow failure (Figure 3.22; image 2).

The Whitecliff Bay landslide shows higher undrained shear strengths than the Red cliff landslide and this could be due to the fact that all the samples are near their plastic limits (Table 3.17), as Andrade et al. (2011) that the shearing resistance of a clayey material will be at its highest near its plastic limit. However, samples from the Red cliff landslide are close to their plastic limits but show very low undrained shear strengths. This could be due to them having a lower clay content than the samples from the Whitecliff Bay landslide and thus this could show the effects that clay content will have on the magnitude of shear resistance when a clayey material is at or near its plastic limit. However, it is worth noting that that the particle size analysis data show the samples having very coarse sand percentages but with the samples being sieved to 1mm and the GRADISTAT programme classing very coarse sand as between 1mm and 2mm (Blott and Pye, 2001), there then shouldn't be any very coarse sand percentages recorded. Thus, the particle size distribution plots are probably in accurate and the clay percentages may actually be larger and therefore they should be used as relative indicators not absolute figures.

The results are slightly conflicting and this is most likely due to an error in the sampling method as the majority of the samples were taken from the surface of the landslides in slipped material. If more samples were taken from the backscars of the landslides then a better relationship could be made between the failed material (body and toe) and the un-failed material (back scar).

The undrained shear strength results from the landslide in Whitecliff generally show a better relationship that the displaced material is weaker than the unfailed material towards the back of the landslide but again this relationship would have been strengthened if more tests were carried out in the back scar region of the landslide. The cohesion factor for these samples are generally higher than the samples from the Red cliff complex landslide but the landslide is of mud slide / flow type not rotational which contradicts Frattini and Crosta (2013) stating that cohesion effects favour large (deeper and longer) landslides, which is what the complex landslide at Red Cliff is. This then could support the fact that the dip of the lithology is having a greater influence on the resultant movement type, as previously stated, than the nature of the lithology itself.

The angle of internal friction of the materials show that for the majority of the material occurring in the main body of the red cliff landslide (Figure 3.22), the friction angels are lower than for the back scar (sample 6, Table 3.14). This supports the fact after failure occurs the angle to which a clay becomes unstable is less than its original angle in previously unfailed state (Forster et al. 1994). However, the effects of cohesion also need to be taken into account, due to its effect as by Andrade et al. (2011), and the samples taken from the front of the slide (S1 & S2, Figure 3.22) show the highest angles of internal friction (Table 3.14) contradicting this relationship. The problem is due to the direct shear box test being a simple test when undrained conditions are carried out on clay samples and cannot account for the effects of pore water pressures (Wu, 1996) and could explain why there appears to be little relationship between the strength parameters. Thus, a better test of these parameters would be a Triaxial test as suggested by Selby (1993) or an unconfined compression test could be used (Barnes, 2010) to compare with the shear vein tests but the apparatus to carry out these tests were not available at Plymouth University.

Overall, the tests generally show that the failed material is weaker than the un-failed material and thus further failure is likely to continue on the landslides, which is supported by the fact that younger failures were identified during the geomorphological mapping of the red cliff landslide (Figure 3.22). However, the properties of the failed material vary over the entire area of the red cliff landslide and thus each area will fail at different times under different circumstances. Also, the generally higher undrained shear strength of the material forming the landslide in Whitecliff Bay, explains why recent younger failures were not seen when geomorphological mapping the landslide.

4.5 Morphology and nature of landsliding

The single rotational slides in the area show typical hummocky features (Figure 3.5) caused by the rotation of the displaced mass along a curved rupture surface (Cruden and Varnes, 1996). These hummocks were also picked out by the profiles (Figure 3.9), shown by the convex part of the profile. The single rotational slides are shallow failures when cliff heights are relatively low but get increasingly deeper seated with larger run outs and offsets as cliff height increases (Figure 3.18-3.21). There is a strong relationship in the data shown by the R^2 values but the strongest relationship can be made between cliff height and vertical offset as there is only about a 10% chance that other factors are causing this relationship (Wheeler et al. 2004). This is similar for cliff height and total length of the landslides, as there is only about a 26% chance that this relationship occurred by other factors. This is understandable as the cliff height will control the amount of accommodation space available and thus the size of the mass that fails in a landslide (Jenkins et al. 2011). The weakest relationship is between cliff height and horizontal offset as there is a much greater chance that other factors such as the lithology are influencing this relationship (about 33%). The majority of the landsliding in the area is complex in nature, which is probably due to the great variation of lithology over the entire area and the complex physical properties of the materials which is highlighted by the previously discussed red cliff complex landslide. The main movement of this landslide is believed to be rotational as the toe area of the displaced mass shows rotation and that ponded water has developed behind the toe of the landslide, which is typical evidence of a rotated block as the block is usually backward tilted creating a depression for water to pond (Varnes, 1978). However the complexity of the surface morphology of the landslide indicates that it is not the only movement type occurring in the landslide and that shallow flows and mud slides have occurred onto the block as shown by the geomorphological map (Figure 3.22). The morphology of the landslide also indicates that it was not a single failure but a series of failures, which is also highlighted by the Google earth imagery showing that the landslide has enlarged in width between 1999 and 2005 (Figure 3.22). This then suggests that the surface of rupture for this landslide has widened and possibly retrogressed (Cruden and Varnes, 1996), which is most likely due to the physical properties of the material. The larger landslide immediately north of the mapped landslide is also Complex. The initial movement of the landslide is believed to be multiple rotational due to two clear hummocks showing up on the profiles of the landslide (Figure 3.9). However, it is Complex due to the back scar of the landslide being active in the form of flows and this is due to the scarp being steep and unsupported providing the condition for new failures (Varnes, 1978). Varnes (1978) also states that steep back scars should provide the potential for the same failure to occur and there is this possibility as the landslide is believed to have been continuously active since 1912 (Hutchinson, 1965, in Jenkins et al. 2011). The fall type landslides in the area show typical accumulations of debris aprons at the base of the slope forming fan shaped cones (Flageollet and Weber, 1996) and are typically constrained to the chalk cliffs at culver cliff.

Flow and translational (planar) landslides are inherently different in their classification but in the case of this study some that have been classed as either flow or translational (planar) will show characteristics of the other type. This is highlighted by the mud slide / flow that was mapped in Whitecliff (Figure 3.25). It consists of features typical of a mudslide characterised by Brunsden and Ibsen (1996) such as the elongate channel (shown by the main body) and the accumulation zone (shown by toe area) consisting of lobes. However, the source area doesn’t show the complexity of morphological features which is normally found in a mud slide (Brunsden and Ibsen, 1996). Cruden and Varnes (1996) does state that there is often a gradation from slides to flows depending on the water content, mobility and evolution of the movement. Thus this appears to be the case for this landslide and can be said to be the case for landslides in the vicinity of Whitecliff especially the landslides that have been classified as complex and with main movements of either translational (planar) or flow (see appendix C). This is supported by the fact that the profiles for the two types of landslides are also very similar, implying they can be interchangeable (Figure 3.8). Also, Brunsden and Ibsen (1996) state that mud slides require suitable materials in order to occur such as overconsolidated clays, silt-clays and fine clayey sands, and as these form the majority of the study area (Figure 3.11 & 3.12) the flow and translational (planar) can potentially be categorised as mudslides.

Chapter 5: Models of landsliding in the study area

A series of models have been produced to represent the nature, characteristics and causal factors of landsliding in the study area (Figure 5.1-5.3). Each area has a unique landsliding style but the causative factors for landsliding in the area are the same with a degree of variability, for example, marine processes will erode and remove material from the base of the slope, which can initiate failure but in front of the Ferruginous sands in Sandown Bay (Figure 5.1), the sea is not eroding the base of the slope and thus explains to an extent why little landsliding has occurred in the Ferruginous sands.

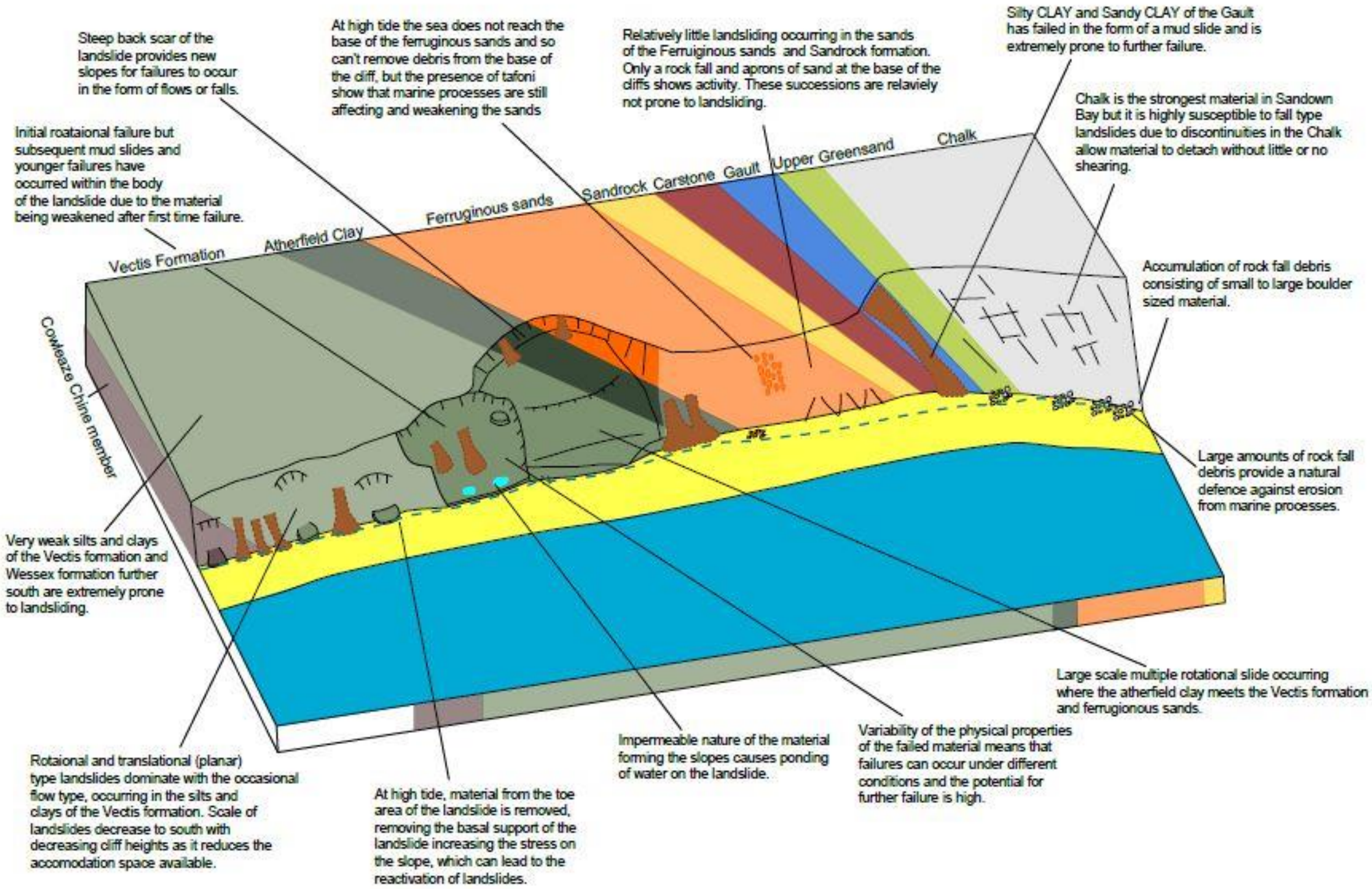


Figure 5.1 Model representing the nature, characteristics and causes of landsliding in Sandown Bay.

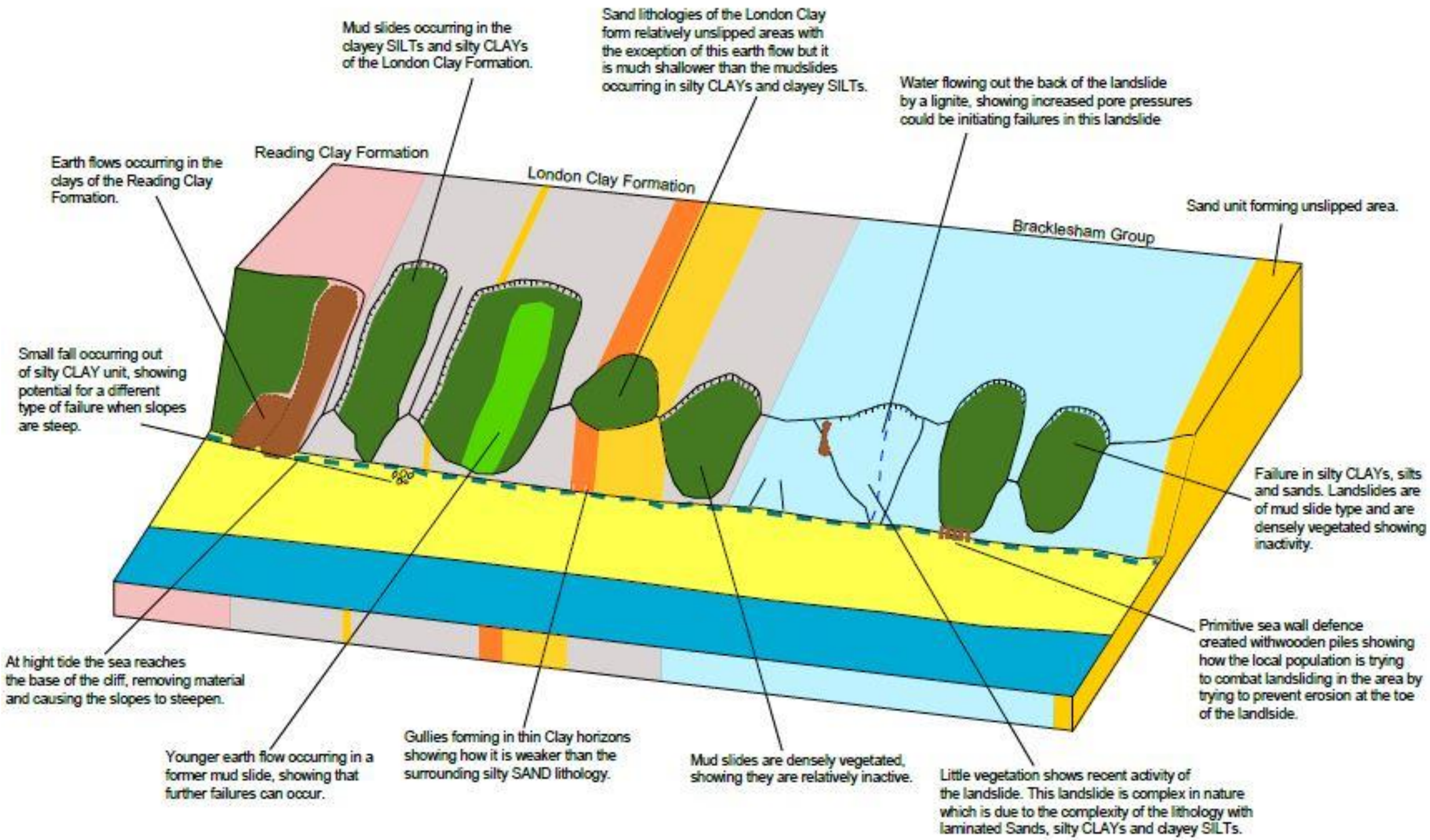


Figure 5.2 Model representing the nature, characteristics and causes of landsliding in Whitecliff Bay (south).

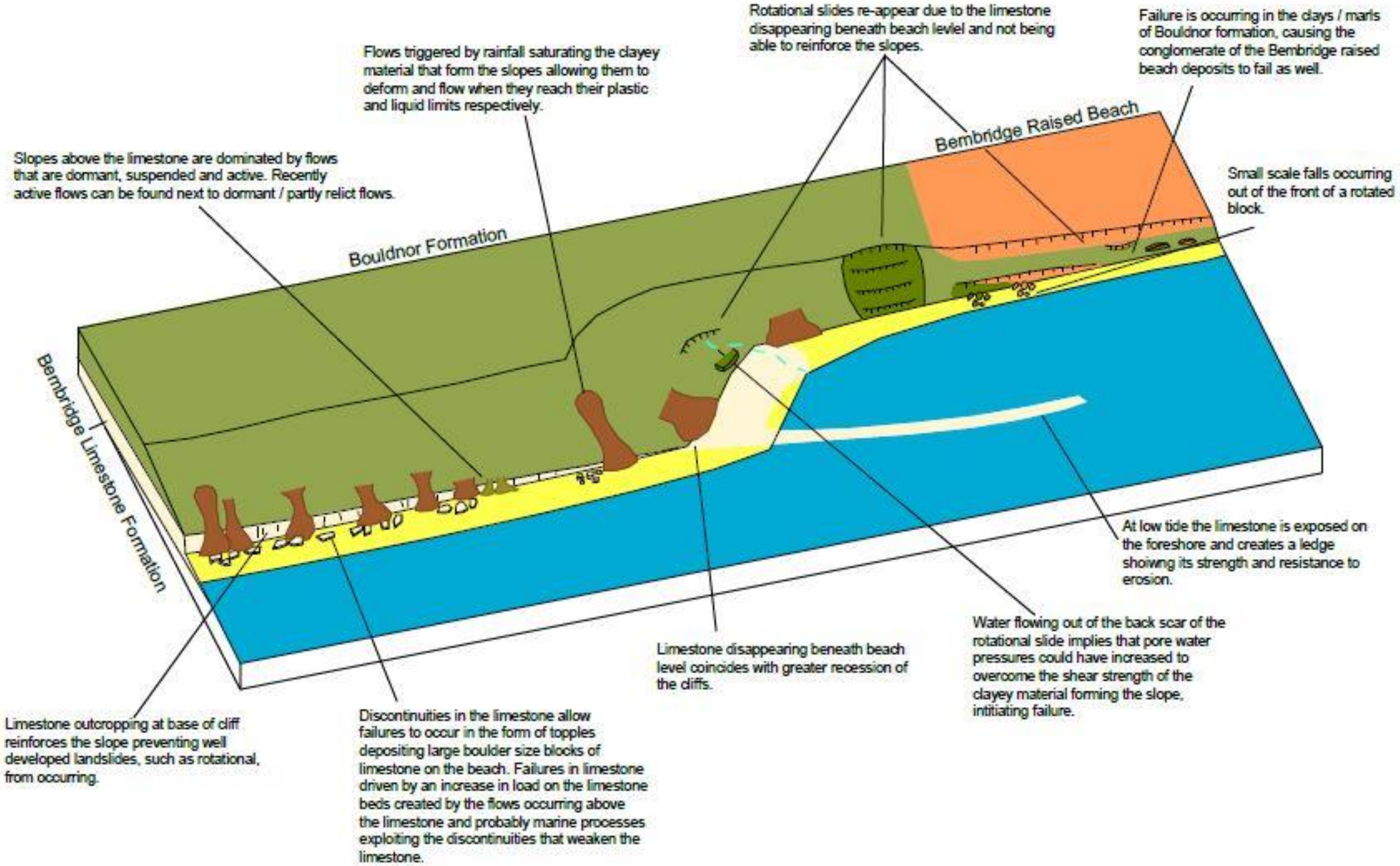


Figure 5.3 Model representing the nature, characteristics and causes of landslding in Whitecliff Bay (north) and Howgate Bay.

However, in Whitecliff Bay (north) (Figure 5.3) where the sea reaches the base of the cliff in the whole area, the limestone of the Bembridge limestone formation is resisting marine erosion and protecting the base of the slope, reinforcing it, but landsliding is still occurring on the slopes above it. This is due to continuous rainfall increasing the water content of the materials in the slope causing mud slide/flows to occur and shows when one factor is not prevalent other triggering factors are. The nature of landsliding varies across the entire area. Despite the majority of the area having suitable materials for mud slides to occur it is only a dominant process in Whitecliff Bay (south) and this is due to the near vertical dipping lithology in Whitecliff Bay (south) (Figure 5.2). Similar materials are present in Sandown Bay but the area is dominated by rotational slides and this coincides with the lithology dipping gently to the north not steeply and further evidence of this effect is the appearance of a mud slide in the Gault Clay which is dipping steeper than similar materials before it. Further evidence for this relationship is that rotational sliding is dominating in Howgate Bay where the lithology is dipping gently to the north. However, when there is a material with greater strength such as the Bembridge limestone, it reinforces the slopes preventing rupture surfaces from occurring and landsliding only occurs in the form of flows or mud slides.

Chapter 6: Conclusion and wider implications

The majority of the study area shows landsliding is a dominant process occurring in the cliff slopes and this is due to the area consisting of weak, poorly lithified sedimentary rocks making them highly susceptible to landsliding. Even when stronger more resistant rocks are prevalent (Chalk) it is still highly susceptible to landsliding due to its physical nature (discontinuities). The topography of the area is also influencing landsliding as it is providing the accommodation space for the displacement of material to occur through landsliding. However, these are just preparatory factors for landsliding, the actual triggering mechanism for landsliding in the area is due to continuous, sometimes intense rainfall, saturating the materials forming the slopes, allowing them to deform and move once their liquid limit is reached but also due to it increasing pore water pressures which can overcome the shear strength of a material triggering a landslide. Marine processes are also a possible triggering factor as high tide reaches the base of the cliffs in most of the area, which removes material from the base of the slopes and thus the slopes basal support increasing the stress on the slope which can overcome the shear strength of the material forming the slopes causing failure to occur as a landslide. The majority of the landsliding in the area are of a complex type due to the majority of the slopes not consisting of a single homogenous lithology. The structure and lithology of the area are having a strong influence on landslide type but the structure of the area is having a slightly stronger influence, due to lithologies that are of a similar nature are not continually producing the same movement type across the area. When stronger more resistant lithologies are forming at or near the base of the slope it acts to reinforce the slopes above and resist marine erosion, however, landsliding does still occur above the more resistant lithology due to high rainfall. These resistant lithologies also act to prevent rupture surfaces from occurring in the slope above and tend to fail as just flows.

The physical properties and shear strength parameter study highlights how variable the materials become after failure has occurred and the material becomes inherently weaker, which will have the effect that allowing continued landsliding on slopes that have already failed. However, this finding would be strengthened if more samples were taken from unfailed areas of the landslides and that more appropriate tests should be carried out to determine the shear strength parameters, which highlights the limitation of these tests. Also, the triggering mechanisms are to a degree inferred and thus further study into the relationship between rainfall and landslide frequency of the area would further support or not support that rainfall is a major triggering factor into landsliding in the area. There is also the potential for further study into the rates at which material is removed by marine processes which can give an indication of how frequent landsliding is most likely to occur.

The findings of this report has implications for the future as the principal causes of landsliding in the area are marine processes and rainfall; the rise in sea level and potential increase in precipitation predicted by the IPCC will mean that landsliding will be a continuous process in the area and a continuous hazard to the public that walk near the top or base of the cliffs, especially the Ferruginous sands and the Chalk. There is then the need for continuous monitoring of the landsliding in the area and there is future potential for further research into the frequency of landsliding events in the area and how landsliding might evolve with future climatic change and sea level rise.

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