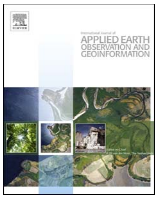
Int J Appl Earth Obs Geoinformation 67 (2018) 79–95

Contents lists available at ScienceDirect

Int J Appl Earth Obs Geoinformation

journal homepage: www.elsevier.com/locate/jag



A combined field/remote sensing approach for characterizing landslide risk in coastal areas

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ARTICLE INFO

Keywords:
Remote sensing
Landslide risk
LiDAR
GIS
Coastal instabilities
Listric faults

ABSTRACT

Understanding the key factors controlling slope failure mechanisms in coastal areas is the first and most important step for analyzing, reconstructing and predicting the scale, location and extent of future instability in rocky coastlines. Different failure mechanisms may be possible depending on the influence of the engineering properties of the rock mass (including the fracture network), the persistence and type of discontinuity and the relative aspect or orientation of the coastline. Using a section of the North Coast of Cornwall, UK, as an example we present a multi-disciplinary approach for characterizing landslide risk associated with coastal instabilities in a blocky rock mass.

Remotely captured terrestrial and aerial LiDAR and photogrammetric data were interrogated using Geographic Information System (GIS) techniques to provide a framework for subsequent analysis, interpretation and validation. The remote sensing mapping data was used to define the rock mass discontinuity network of the area and to differentiate between major and minor geological structures controlling the evolution of the North Coast of Cornwall.

Kinematic instability maps generated from aerial LiDAR data using GIS techniques and results from structural and engineering geological surveys are presented. With this method, it was possible to highlight the types of kinematic failure mechanism that may generate coastal landslides and highlight areas that are more susceptible to instability or increased risk of future instability. Multi-temporal aerial LiDAR data and orthophotos were also studied using GIS techniques to locate recent landslide failures, validate the results obtained from the kinematic instability maps through site observations and provide improved understanding of the factors controlling the coastal geomorphology. The approach adopted is not only useful for academic research, but also for local authorities and consultancy's when assessing the likely risks of coastal instability.

1. Introduction

Discontinuity-controlled slope instabilities are an important natural hazard that can affect hard rock coastlines in blocky rock masses. Different failure mechanisms may be kinematically feasible depending on the influence of the rock mass fracture network (geometry and engineering characteristics of identified fracture sets that form a three dimensional fracture network) and the relative orientation of the coastline to the fracture network. The study of coastal failure involves evaluation of several contributing factors such as underlying failure and erosion mechanisms, changes in environmental (weather and sea) conditions, variations in coastline morphology, geology and structural geology, etc. (Collins and Sitar, 2008; Wolters and Müller, 2008; Abellán et al., 2009; Naylor et al., 2010; Stock et al., 2012). The analysis and prediction of such failures can be challenging as it is also important to consider the spatial and temporal aspects of failure as well as scale, size, impact and consequence.

Several recent studies have identified the potential use of remote sensing techniques for improved understanding of coastal processes, although most investigations are associated with relatively small scale studies. For example, at a scale of several kilometres Rosser et al. (2013) showed the use of multi-temporal terrestrial laser scanning for analyzing precise failure patterns across near-vertical rock cliffs on a section of the UK North Sea coast. Although the precise patterns highlighted by their research is specific for the site studied, the underlying progressive incremental failure mechanism proposed can be applied to wider applications. More recently, Mantovani et al. (2016) highlighted the use of InSAR techniques and developed a methodology

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https://doi.org/10.1016/j.jag.2017.12.016
Received 12 August 2017; Received in revised form 24 November 2017; Accepted 30 December 2017

Fig. 1. A) 3D Google Earth image of Cornwall with study area highlighted in black (inset shows a map of United Kingdom with Cornwall highlighted in red). B) Area of study between Hell's Mouth and Portreath on the North Coast of Cornwall. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 2. Photographs of Hell's Mouth failure area prior to failure and two subsequent episodes of instability. Comparison of photographs taken on 23/09/2011 and 24/12/2011 show further instability of the South-West section of the failure area a few weeks after the main landslide that was captured on video (photograph taken looking towards NE).

for automatic classification of radar reflectors phase histories. Using this approach, the authors were able to interpret the kinematics and displacement trends of slow-moving coastal landslides in a sector of the island of Malta. The combined use of InSAR and UAV techniques is described by Mateos et al. (2017) for monitoring of a landslide affecting the urban development in the Cármenes del Mar Resort.

When applying these techniques to a larger/regional scale a wider area has to be studied and more information considered. Application of InSAR can be often be problematic because of the absence of natural scatter areas, presence of vegetation, unavailability of images, unsuitable satellite return periods, cost and complexity of post-processing. Dickson and Perry (2016) recently presented the use of a machine-learning approach for analyzing coastal cliff landsliding in a large portion of New Zealand using an existing landslide database containing 498 landslides. This purely-statistical based research (where cliff and bedding geometry, lithologies, slope degree/aspect/exposure and proximity to faults were used as predictors) highlighted that in the studied area, landsliding generally occurs at sites where faults intersect cliffs with high slope angle.

In this paper, we provide a regional scale analysis of coastal instability that includes identification of recent landslides and highlights the influence of structural geology on the likely scale of potential instability. This is performed using conventional predictors (such as cliff and bedding geometry, lithologies, slope degree/aspect/exposure) with information relating to the structural setting of the area (type and shape of faults and fracture sets). We use a section of the North Coast of Cornwall, UK (Fig. 1A), between Hell's Mouth and Portreath, shown in Fig. 1B, to demonstrate how the combined use of several disciplines (geology, structural geology, GIS, remote sensing) provided a multi-scale analysis of coastal instability in blocky rock masses. Specifically, the proposed multi-disciplinary approach emphasizes the integrated use of conventional geological/engineering surveys, aerial and terrestrial remote sensing and GIS together with validation through engineering geological mapping and site observations. Special emphasis is given to the evaluation of the role of major faults in controlling the volume/type of failures and the geometry or geomorphology of the coastline. Two 'site-specific' investigations showing the importance of structural geology in the analysis of slope failures are illustrated by Humair et al. (2013) and Brideau et al. (2009) in the analysis of the Turtle Mountain (Alberta, CA), Hope Slide (British Columbia, CA) and Randa Rockslide (Switzerland). Using a similar approach, this has been extended in the current research to a more regional scale study.

Aerial LiDAR and photogrammetry were used to identify major structures in the study area. This data was then integrated with field data (traditional engineering geological and remote sensing surveys) to generate a discontinuity database that included both major and minor structures.

GIS was used in this study to improve the interpretation of remote sensing data and develop kinematic instability maps. Other research showing the use of GIS and remote sensing in landslide and structural geology investigations has been presented by Jaboyedoff et al. (2004), Oppikofer (2009), Brideau et al. (2011), Fey et al. (2015) and Francioni et al. (2015, 2017).

Finally, to identify recent landslides that have occurred in the immediate area of study and validate the results obtained from the GIS analysis, two aerial LiDAR datasets, 2011 and 2014 (available through