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Cost-effective erosion monitoring of coastal cliffs

Matthew J. Westoby[a], Michael Lim[b,*], Michelle Hogg[c], Matthew J Pound[a], Lesley Dunlop[a], John Woodward[a]

[a] Department of Geography and Environmental Sciences, Northumbria University, Newcastle upon Tyne, NE1 8ST, UK
[b] Department of Mechanical and Construction Engineering, Northumbria University, Newcastle upon Tyne, NE1 8ST, UK
[c] South Tyneside Council, South Shields, NE33 2RL, UK

A R T I C L E I N F O

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A B S T R A C T

Structure-from-motion with multi-view stereo (SfM-MVS) methods hold the potential for monitoring and quantifying cliff erosion to levels of accuracy and precision which rival terrestrial laser scanning (TLS) and at a fraction of the cost. We benchmark repeat SfM-MVS against TLS for quantifying rock fall frequency, volume, and cliff face erosion rates for a ~1 km section of coastal cliffs where cliff top infrastructure is threatened by erosion. First, we address a major unknown in these techniques, the number and configuration of control points. Surveys demonstrate that a sparse configuration along the cliff base and top, at spacing equivalent to the cliff height, provides suitable accuracy at acceptable logistic time and expense. Second, we show that SfM-MVS models match equivalent TLS data to within 0.04 m, and that the correlation between intersecting TLS- and SfM-derived rock fall volumes improves markedly above a detection threshold of 0.07 m^3. Rock falls below this size threshold account for ~77.7% of detected rock falls but only 1.9% of the calculated annual eroded volume. Annual erosion rates for the 1 km cliff face as calculated by repeat TLS and SfM differencing are 0.6×10^{-2} m a^{-1} and 0.7×10^{-2} m a^{-1}, respectively. Kilometre-scale patterns of cliff erosion are dominated by localised zones of high-magnitude, episodic failure that are over an order of magnitude greater than background rates. The ability of non-specialist engineers, geologists, geomorphologists and managers to rapidly capture high quality, accurate erosion data in a cost-effective manner through repeat SfM-MVS has significant potential to inform coastal managers and decision makers. To further empower coastal authorities and communities, policy frameworks must be developed to incorporate and interpret these data.

1. Introduction

Significant investment is made into mitigating the risks posed by coastal erosion to buildings, infrastructure, utilities and ecosystems in the coastal zone. For example, an estimated GBP >50 million is invested annually by the UK government to delay coastal erosion in England and Wales (Penning-Rowsell and Pardoe, 2015) whilst annual EU public expenditure on coastline protection during the period 1990 to 2020 from risks posed by coastal flooding and erosion is expected to exceed EUR 5.4 billion (European Commission, 2006). Fundamental to the development of effective coastal management options is a well-developed understanding of rates of coastal erosion, their temporal and spatial distribution, and how these may change under future scenarios of climatic change (Dawson et al., 2009). The challenges of optimising the distribution of funding to combat coastal erosion are further enhanced by widespread policy shifts from holding the existing coastline to a range of managed retreat scenarios (Dickson et al., 2007).

Rates of coastal erosion are used alongside future sea-level rise scenarios as key inputs into predictive models for assessing the coastal erosion risk, often at the regional to national scale (e.g. (Bray and Hooke, 1997; Davidson-Arnott, 2005; Environment Agency, 2009; Hall et al., 2003; Mulder et al., 2011; Nicholls et al., 2013; Pethick, 2001)). Estimated or observed rates of coastal retreat are an internationally recognised severity measure for coastal erosion and are typically used to inform coastal development and management (Roebeling et al., 2013; Pranzini et al., 2015; Lazarus et al., 2016; Thieler and Danforth, 1994a). Specifically, these data form the basis for forecasting future coastal recession, where historic retreat rates are extrapolated in conjunction with models of future sea-level rise, typically using the 'Bruun rule' (Bruun, 1962; Cooper and Pilkey, 2004), to identify areas that are exposed to the greatest erosion risk and inform decisions about future management.

* Corresponding author.
E-mail addresses: mjwestoby@gmail.com (M.J. Westoby), matt.westoby@northumbria.ac.uk (M. Lim).

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Table 1
Summary of survey methods used to quantify coastal erosion.

Data source or method	Pros	Cons	Example references
Cartographic mapping	Often cover large spatial scales (>10 km). Typically freely available or at low cost.	Subject to mapping inaccuracies which hinder accurate delineation of shoreline or coastline in regions of complex topography. Generally no systematic map production interval. Map resolution often not sufficient for detailed erosion monitoring, i.e. where erosion rates are low.	(Brooks and Spencer, 2010; Dornbusch et al., 2008; Genz et al., 2007; Oyedotun, 2014; Sear et al., 2011; Thieler and Danforth, 1994b)
Aerial photography and photogrammetry	Production of detailed, fine-resolution (≤decimetre) orthoimagery.	Expensive to acquire. Survey interval dictated largely by cost. Requires skill in photogrammetric processing to generate accurate datasets.	(Baily and Nowell, 1996; Costa et al., 2004; Dewez, 2004; Moore, 2000; Moore and Griggs, 2002; Pierre, 2006)
Satellite imagery (optical)	Some products freely available. Can cover large, typically regional, spatial scales.	Freely available imagery is often of coarse resolution (>decimetre). Fine resolution (<decimetre) imagery costly for most coastal monitoring and management projects. Usable imagery hindered by cloud cover.	(Loos and Niemann, 2002; Maiti and Bhattacharya, 2009; Pardo-Pascual et al., 2012; White and El Asmar, 1999)
GPS/GNSS	Permits roving capture of cliff-top or cliff-base topography. Relatively affordable and accurate (typically centimetre - decimetre)	Topographic occlusion can affect signal quality, and thus survey accuracy. Difficult to implement around hazardous cliff environments. Time-consuming to acquire data at spatial density which accurately reflects complex topography.	(Baptista et al., 2011; Feagin et al., 2014; Mills et al., 2005; Montreuil et al., 2013)
Airborne LiDAR	Permits direct topographic reconstruction of extensive coastal stretches (>10 km in a single flight). Some data freely available (e.g. UK Environment Agency), but generally not repeat datasets.	Often prohibitively costly to commission. Monitoring interval primarily determined by cost, also weather conditions. Difficult to resolve near-vertical topography (e.g. cliff faces) in sufficient detail due to sensor viewshed.	(Earlie et al., 2015; Obu et al., 2016; Palaseanu-Lovejoy et al., 2016; Pye and Blott, 2016; Young et al., 2011)
Terrestrial LiDAR	Can generate fine-resolution, precise and spatially continuous topographic data. Permits process-scale erosion analysis.	High purchase and maintenance costs. High power requirements and difficult portability. Survey viewshed limited by system line-of-sight. Some advanced knowledge of topographic differencing methods required to produce spatially distributed erosion maps.	(Feagin et al., 2014; Kuhn and Prüfer, 2014; Lim et al., 2005; Montreuil et al., 2013; Rosser et al., 2005; Rosser et al., 2013)
Structure-from-motion (with multi-view stereo)	Low-cost, requires consumer-grade camera and software purchase. Produces fine resolution and spatially continuous 3D topographic data. Minimal deployment time, suitable for rapid and responsive surveying. Accessible, minimal training required to generate fine-resolution 3D models. UAV-mounted camera can be used to monitor in hazardous areas, and extend areal coverage.	Survey control points necessary for georeferencing and accuracy assessment. Must be manually deployed and surveyed. Some advanced knowledge of topographic differencing methods required to generate spatially distributed erosion maps.	(Brunier et al., 2016; Gibbs et al., 2015; Gienko and Terry, 2014; James and Robson, 2012; Mancini et al., 2013; Lim et al., 2015; Turner et al., 2016; Warrick et al., 2017; Westoby et al., 2012)