Geomorphology 191 (2013) 14–22

Contents lists available at SciVerse ScienceDirect

Geomorphology

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

Sea saltwater weakening of chalk and the impact on cliff instability

J.A. Lawrence [a,*], R.N. Mortimore [b], K.J. Stone [b], J.P. Busby [c]

[a] School of Earth and Environment, University of Leeds, Leeds, Yorkshire, LS2 9JT, UK
[b] School of Environment and Technology, University of Brighton, Lewes Road, Brighton BN2 4GJ, UK
[c] British Geological Survey, Keyworth, Nottingham, Nottinghamshire, UK

ARTICLE INFO

Article history:
Received 2 February 2012
Received in revised form 3 January 2013
Accepted 24 February 2013
Available online 4 March 2013

Keywords:
Chalk
Cliff collapse
Salt weakening
Weathering
Climate change impact

ABSTRACT

Chalk forms one of the major coastal cliff formations throughout Northwest Europe, with large population centres and critical infrastructure being exposed to and at risk from cliff collapses in this rock type. Traditionally, the two main factors leading to chalk cliff collapse have been considered to be: (i) waves attacking and eroding the base of the cliff and (ii) water weakening as the chalk becomes saturated. This work challenges the established view by identifying the role of salt from seawater in the degradation of porous rocks in coastal environments as a third and potentially the most important mechanism leading to chalk cliff collapse. Field and laboratory investigations have identified and quantified the role of sea saltwater weakening of chalk in coastal environments. A series of triaxial strength tests have identified that coastal chalks are up to 55% weaker than their inland equivalents. This weakening process is as a result of saltwater ingress into the chalk. SEM imaging has shown that seawater penetrates the porous chalk and the salt progressively concentrates, forming salt crystals which disrupt the pore structure and weakening the rock material which then leads to catastrophic cliff failure. Saltwater weakening of cliffs could be one of the main factors leading to large- and small-scale collapses observed along the chalk coast line, and is likely to be the primary reason for the increasing frequency of cliff failures along protected coastal sections as the sea salt progressively concentrates in the cliff reducing its mechanical strength. Rock strength is not usually considered to be temporally variable and is, therefore, rarely considered in relation to climate change. However, this is not true of soft rocks like chalk, which weaken and collapse in short time periods as they are exposed to external factors.

© 2013 Elsevier B.V. All rights reserved.

1. Introduction

This paper reports on the previously unidentified saltwater weakening mechanism leading to coastal cliff collapse throughout Northwest Europe. Chalk coasts evolve rapidly so this is the ideal rock type to test processes leading to cliff failure which can then be used as a baseline to test any rock type. In the UK alone over 1 million people live within 1 km of chalk cliffs, leaving much of the UK's population and its critical infrastructure exposed to the hazard of cliff collapse and recession (Stavrou et al., 2011). Many of these coastal areas are National Parks, Sites of Special Scientific Interest (SSSI) and/or Geological Conservation Review sites (GCRs). Understanding the mechanisms involved in coastal chalk cliff failure can be used to inform national and local plans for coast protection and infrastructure resilience. In 2004 the Office of Science and Technology published its Foresight, Future Flooding Report (Evans et al., 2004) which took a long-term view of national flooding and coastal erosion risks to 2100. The report estimated that there were at least £10 billion of assets at risk of coastal erosion and climate change over the next 90 years. The entire chalk coast section was designated very high or at extreme risk (the two highest risk categories) of potential shoreline erosion. Evans et al. (2004) calculated that an integrated portfolio of responses could reduce the risks of coastal erosion by up to 90% by the 2080s. However, this still represents double the present-day economic losses.

Chalk cliffs occupy more than 400 km or 10% of the English coastline and approximately 200 km or 5% of the French coastline (Hopson, 2005). Chalk cliffs occur in other parts of Europe such as Germany Ireland and Denmark. At Møns Klint, Denmark, the chalk forms some of the highest cliff sections in Europe and collapses have led to fatalities (Pedersen and Møller, 2004).

This is the first detailed investigation of the effects of salt weakening of chalk cliffs, providing empirical evidence by investigating the amount of salt weakening taking place in chalk cliffs at selected research sites in the UK and France. This involved: i) identifying the causes of seawater ingress and concentration in the rockmass, ii) identification of mechanisms leading to weakening and iii) quantification of the extent of the resulting salt weakening. Traditionally, the two main factors leading to cliff collapse have been considered to be (i) waves attacking and eroding the base of the cliff (Emery and Kuhn, 1982; Mortimore et al., 2004a) and (ii) water weakening as the chalk becomes saturated

---

* Corresponding author. Tel.: +44 113 343 5233; fax: +44 113 343 5259.
E-mail addresses: j.a.lawrence@leeds.ac.uk (J.A. Lawrence), Rory.Mortimore@btinternet.com (R.N. Mortimore), Kevin.Stone@brighton.ac.uk (K.J. Stone), jpbu@bgs.ac.uk (J.P. Busby).

0169-555X/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.geomorph.2013.02.022

(Bell, 1977; Said et al., 2009). This work challenges the established view by identifying the role of salt from seawater in the degradation of porous rocks in coastal environments as a third and potentially the most important mechanism leading to chalk cliff collapse.

2. Previous research

It has been estimated that over 80% of the world coastline is occupied by rock cliffs (Emery and Kuhn, 1982), but because processes develop over very long time periods a lack of field data exists for verification and calibration. Cliffs are frequently classified as either soft or hard depending on the rockmass. Soft cliffs consist of superficial deposits through to bedded and jointed weak rock (Lee and Clark, 2002), whilst hard rocks are considered to be sedimentary cliffs through to resistant igneous cliffs (Trenhaile, 1987). Chalk cliffs are clearly relevant to both groups and therefore of particular importance to understanding processes leading to cliff failure in the broadest occurrence (Moses and Robinson, 2011). Combining this with the relatively rapid chalk coast evolution which makes the study of coastal processes possible and the long sections of chalk cliff throughout Northwest Europe, it becomes clear the chalk cliffs are ideal for this investigation. Cliff stability is dependent on the strength and stand up times of the material, therefore previous studies of the mechanical properties of the chalk summarised in Lord et al. (2002) (Table 1) are key to understanding the behaviour of the rock.

One of the main findings from previous research is the effect of weakening when chalk is saturated with water or oil: the wettability of chalk (Standnes and Austad, 2000; Risnes et al., 2003). Authors have identified this liquid wettability mechanism as leading to weakening; however, the causes are not well understood. This effect could be related to the chemistry of the liquid and its reaction with chalk pore structure and has been discussed in relation to spalling masonry by Robinson and Jerwood (1987) (Table 2). The role of salt weathering in coastal environments is highlighted by Trenhaile (2008) who identified that weathering can play an important indirect role in the quarrying of jointed rocks. Whilst Trenhaile's (2008) work has focused on the shore platform, the same should be true for waves acting on the base of the cliff. Sea-salt weathering effects the rock by causing disruption as the salt crystallises, but uniquely to limestones (including chalk) a second mechanism by dissolution of the calcareous cement has been identified (Cardell et al., 2003). Therefore, two main types of salt weakening may affect the strength of the cliff:

1. Physical attack (haloclasty): This results from salt crystallisation (NaCl). It has been identified within rocks and masonry and in the chalk along coastal sections (Jerwood et al., 1990; Busby et al., 2004).
2. Chemical salt weathering: It is known that water weakening takes place in the chalk through chemical dissolution (Fookes and Hawkins, 1988). However, seawater may further contribute to the weakening as the magnesium (Mg^{2+}) and sulphate (SO_4^{2-}) from seawater concentrates in the rock and the SO_4^{2-} acts as a catalyst for the substitution of calcium (Ca^{2+}) from the chalk by Mg^{2+}. When this substitution occurs at grain boundaries the different size of the Ca^{2+} and Mg^{2+} may cause stress and a decrease in the mechanical strength of chalk (Heggheim et al., 2005; Austad et al., 2008).

Table 1
Previous triaxial tests on intact specimens of chalk.
After Lord et al. (2002).

Reference	Location	Type of triaxial test	Sample size
Leddra and Jones (1990)	Hampshire	Undrained	38 mm
Fletcher and Mizon (1984)	Ipswich	Drained	100 mm
Burland et al. (1983)	Salisbury	Drained	100 mm
Hutchison (1971)	Isle of Thanet	Drained	38 mm

Table 2
Summary of the research results demonstrating fluid saturation causing reduction in the strength of carbonate rocks.

Reference	Summary of work
Robinson and Jerwood (1987)	Identified chemical attack related to sulphate ion occurrence in the development of cracking and spalling masonry in carbonate rocks
Risnes et al. (2003)	Found water activity was a contributing parameter in the water-weakening mechanisms
Busby et al. (2004)	Loss of strength in salt water-saturated chalks and a increase in strength of dry samples during triaxial testing
Duperret et al. (2005)	Suggested seawater weathering led to a reduction in strength because of disaggregation as a result of salt crystallisation in the chalk matrix
Heggheim et al. (2005)	Found brine-saturated chalk in oil reservoirs was rapidly undergoing a chemical dissolution reaction at grain scale, resulting in a loss in strength

Bell (2000) and Benavente et al. (2008) suggested that there are three ways in which a rock could breakdown as a result of salt weakening:

- The pressures produced by crystallisation in pores. Crystal growth has been shown to exert over 20 MPa of pressure; this is easily sufficient to disrupt the chalk through crystal wedging;
- Disruption in the rock may take place due to considerable contrast in thermal expansion of salts crystallising in pores;
- Hydration pressure that depends on the ambient temperature and the relative humidity exerts additional pressure.

The effects of saltwater on chalk strength were briefly commented on in Busby et al. (2004) leading to this comprehensive investigation. Duperret et al. (2005) illustrated seawater degradation of chalk using cycles of wetting and drying, but conducted only one triaxial compression test. Heggheim et al. (2005) showed that ageing chalk in brine also produced a reduction in overall strength. However, results from Risnes et al. (2003) suggested the opposite effect; they observed that as more salt was added to the saturating liquid, very slight strengthening of the chalk occurred. It is likely however that the relatively low concentrations of salt-saturating liquid used by Risnes et al. (2003) to saturate the samples did not affect the matrix or the strength of the chalk (Table 2).

3. Sampling strategy and research sites

Chalk blocks were excavated from the cliff face at selected coastal research sites in the UK and France. In addition an inland stratigraphical equivalent research site unaffected by salt from seawater was sampled. On collection, the samples were wrapped in aluminium foil to prevent moisture loss on transportation back to the laboratory. This was found to be better than putting the samples in sealed plastic bags which causes the sample to sweat (Mortimore et al., 2004b). In situ representative samples were collected and the block orientation (strike, dip and way up) was recorded. Larger samples were preferred as more cores could be obtained from a single source, which was likely to give more consistent measurements. Hence samples over 20 kg in weight were collected.

Geological logging was conducted to establish the relationships between the rock properties, chalk formations, the different research sites and to select formations which were representative of large sections of the chalk cliff coast throughout Northwest Europe. In the UK and France samples were collected from 4 localities (Table 3):

1. Birling Gap, East Sussex, UK [Ordnance Survey grid co-ordinates TV 5544 9593]: Stratigraphically this is in the Seaford Chalk Formation within the Cuckmere Beds.

Download English Version:

https://daneshyari.com/en/article/4684808

Download Persian Version:

https://daneshyari.com/article/4684808

Daneshyari.com