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Modeling cyclic recession of cohesive clay coasts: Effects of wave erosion and bluff stability

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ABSTRACT

A mathematical model combining the effects of wave erosion, beach sediment, and bluff slope stability has been developed to study the episodic, cyclical recession of cohesive clay coasts. The model was applied to the southern Great Lakes in North America which, although non-tidal, experience seasonal fluctuations in lake level of about 0.5 m and long-term fluctuations of up to 2 m. Model runs were designed to explore the interaction between various components of the system, including profile shape, bluff recession rates, lake level variations, beach morphodynamics, the geomechanical characteristics of the material, and the type (slump, topple) and size of the slope failures. Model runs were made for the equivalent of 100 years. Quasi-equilibrium conditions developed in the runs, which had similar erosion rates to the field, with parallel slope retreat in the upper portion of the profiles and slope decline in the lower portion. Temporal variations in the rate of recession of the crest of the bluff closely matched changes in lake level. The model confirmed previous work that suggested that rates of bluff recession are strongly controlled by the rate of erosion below the water surface, but it also provided support for a more recent proposal that rates of bluff recession also influence rates of erosion in shallow water. It was found that positive and negative changes in the size of the beach can either promote or hinder bluff and profile erosion depending on local circumstances. The model demonstrated that bluff height, debris mobility, wave undercutting, and groundwater levels are key factors in determining the stability of coastal bluffs. The model represents a promising new tool to forecast and thereby mitigate the effects of climate change on marine and lacustrine coasts.

1. Introduction

There are clay coasts in many parts of the world, but they are particularly extensive in glaciated regions, including around the North and Baltic Seas in northern Europe, the Great Lakes in North America, and in parts of the northeastern United States. There is a concern over the effect of rapid erosion and bluff instability on the lives, property, and infrastructure of growing populations along clay and other soft rock coasts that have low resistance to wave attack, weathering, and mass movement. These existing problems will be exacerbated in the future by rising sea level and possibly increased storminess associated with climate change. The ability to predict coastal recession and the response of cliffs to changing environmental conditions and to anthropological pressures and activities is therefore a fundamental requirement for coastal management and planning.

Clay bluff erosion and recession is a function of the geotechnical properties of the materials and wave erosion on the lake or sea bottom and at the foot, or toe, of the bluff. Toe erosion triggers a variety of landslides that occur with different frequencies and durations. Attempts have been made to predict clay bluff recession rates and to identify relationships between the causative factors. Predictions have been based on historical rates of recession and on a variety of empirical and probabilistic methods (Bray and Hooke, 1997; Hall et al., 2002; Sallenger et al., 2002; Lee, 2005; Collins and Sitar, 2008; Furlan, 2008; Hapke et al., 2009). There have also been many attempts to model the development, and to predict the erosion, of clay coasts (Parthenaides, 1965; Dick and Zeman, 1983; Kamphuis, 1986; Nairn et al., 1986; Healy et al., 1987; Kamphuis, 1987; Lee et al., 2001; Walkden and Hall, 2005; Trenhaile, 2009), and several models have been modified to consider the effect of rising sea level (Dickson et al., 2007; Walkden and Dickson, 2008; Trenhaile, 2010, 2011).

Most models have been concerned with the erosional effect of wave-generated turbulence, abrasion, and hydrostatic pressure variations beneath shoaling waves and surf (Coakley et al., 1986; Bishop et al., 1992; Skafel and Bishop, 1994; Skafel, 1995). There has been less attention paid to the direct effect of wave, surf, or swash impact on bare clay platform surfaces and on the role of changing beach morphology in determining the frequency and strength of run-up impacts on the bluff. Wave erosional models have generally considered the

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response of clay cliffs to wave undercutting in a simplistic manner, whereas wave dynamics have been ignored or treated superficially in models and other investigations concerned with bluff failure mechanisms and characteristics (Hutchinson, 1970; Bromhead, 1978; Dixon and Bromhead, 2002; Vandamme et al., 2012). No model has yet integrated the marine and subaerial domains to explore interrelationships between wave and beach dynamics and cliff material properties and failure mechanisms, and to account for episodic and cyclical coastal recession.

The present paper is concerned with the formulation and testing of a model which, for the first time, considers the combined effect of wave erosion and slope failure on clay coast dynamics. This model shares some of the characteristics of other clay coast models (Dick and Zeman, 1983; Kamphuis, 1986; Nairn et al., 1986; Walkden and Hall, 2005; Trenhaile, 2009; Castedo et al., 2012) but with significant differences that include the effect of run-up strength and frequency on bluff erosion, and geotechnical stability analysis to predict the occurrence, type, and magnitude of slope failures (Quigley et al., 1977; Amin and Davidson-Arnott, 1995; Johnson and Johnston, 1995; Brown et al., 2005; Quinn et al., 2010). The model simulates basal erosion and the resultant effects transmitted by gravitational movements up the bluff to the backscar. This has been achieved by incorporating the classical "Swedish" or "Fellenius" Method of slices (Fellenius, 1936), into a process-response recession model. Although this paper is mainly concerned with the derivation and structure of the model, some examples of model runs for the cohesive clay coasts of the lower Great Lakes of North America are provided to demonstrate how it replicates and predicts clay-coast development (Fig. 1A). More detailed investigations of lacustrine and marine coasts, under stable and positive and negative changes in water levels, and under a greater variety of geomechanical conditions, will be undertaken in the future. The terms 'bluff' and "platform" are used in this paper to refer to steep coastal slopes or cliffs in clay (soft rock) and sloping clay surfaces, or shore platforms, at the cliff foot, respectively. S.I. units are used throughout the paper. Slope failure mechanisms generate cyclical changes in bluff face gradients and, consequently, are a source of variability in bluff recession rate

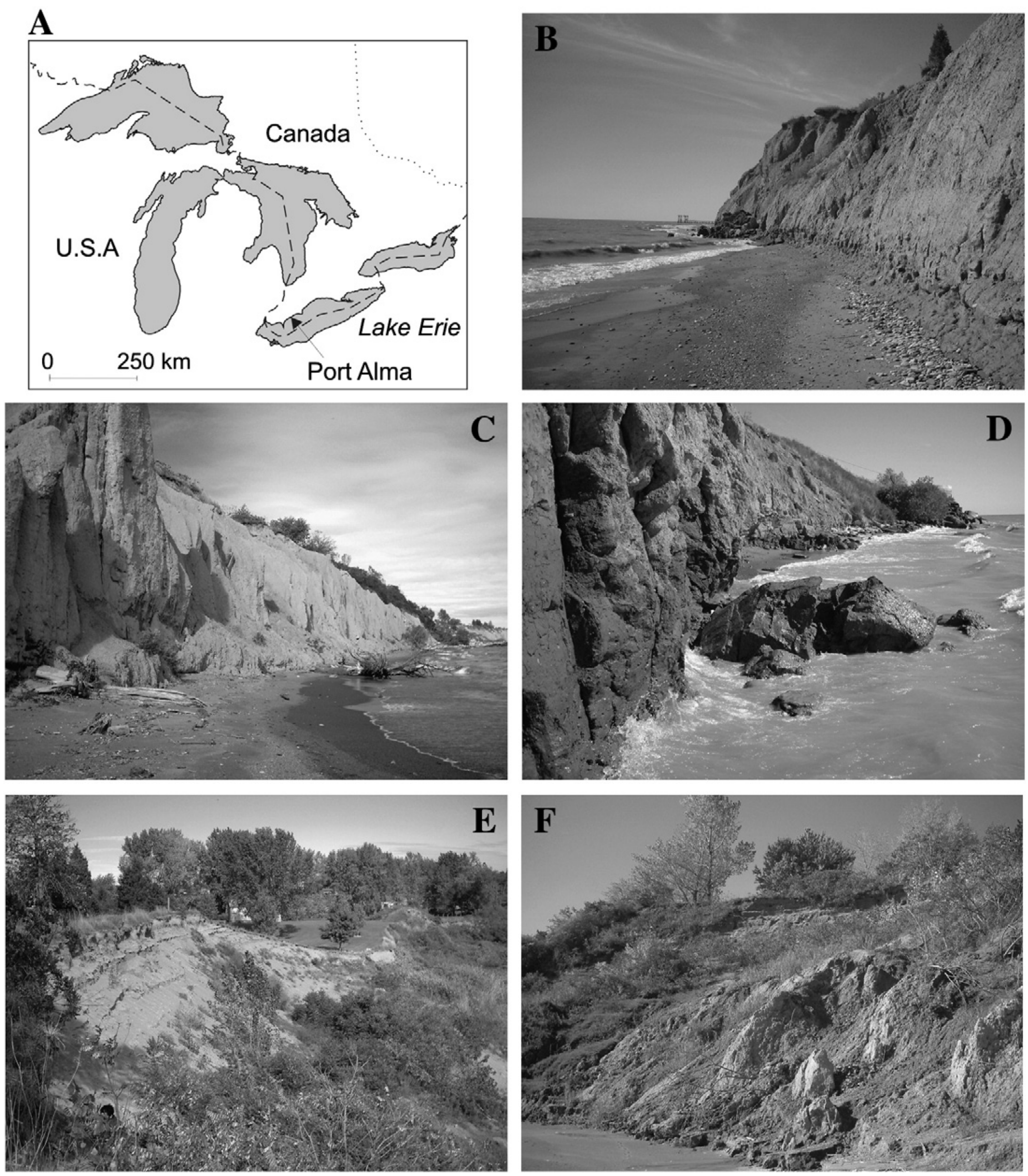

Fig. 1. A) The Great Lakes — photographs are from near Port Alma on Lake Erie; B) till bluff and narrow beach; C) bluff notch and tensile crack preceding toppling (left side of photograph); D) erosion of topple debris; E) slump in high bluffs; and F) eroded slump block.