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Stability of permafrost dominated coastal cliffs in the Arctic

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ABSTRACT

Block failure is considered to be an important component of coastal retreat in permafrost regions. A comprehensive model is developed to study the effects of thermoerosional niche and ice wedge morphology on the stability of permafrost dominated coastal cliff against block failure. The model is formulated by coupling slope stability analysis with a time dependent progression of thermoerosional niches and the morphology of the nearby ice wedges. Model computations are initially performed for failure conditions for a given cliff height, frozen soil strength, ice content, water pressure in the active layer, thermoerosional niche depth and ice wedge morphology. Under these conditions block failures are found to be predominantly overturning failures and are governed by the tensile strength of frozen soil, thermoerosional niche depth and ice wedge location and depth. The effects of ice wedges are then examined by analyzing failure conditions for ice wedges of different locations and depths. For a given cliff height, strength and thermoerosional niche, block failure may occur at a range of different combinations of ice wedge locations and depths. Two stability nomograms are developed through repeated model calculations for range of cliff heights and frozen soil tensile strength. These nomograms can be used to determine the critical combinations of thermoerosional niche depth, ice wedge distance and ice wedge depth that lead to block collapse of a cliff of known height and soil strength. Some analytical expressions are also derived to determine potential block failure criteria along Arctic coasts.

1. Introduction

Arctic coasts characterized by ice-rich permafrost are possibly one of the most sensitive environments (Solomon, 2005) to climate change. Increased rates of erosion along Arctic coasts is related to the synergistic effects of warming permafrost, reduced sea ice extent, longer open water seasons, sea level rise and increased storm activity. The works of Jones et al. (2009) reported that the rate of erosion along a stretch of Alaska's northeastern coastline has doubled over the past 52 years. Leont'yev (2004) predicted that the recession of thermal abrasion cliffs is expected to accelerate by 1.4–1.5 times in the second half of the 21st century. Arctic systems are widely recognized for their vulnerability to perturbations in climate (ACIA, 2005). Highly vulnerable systems like Arctic coasts need to be studied in greater detail and systematically modeled to anticipate and prepare for future changes in Polar environments. Arctic coasts lie at the interface between terrestrial systems dominated by permafrost and marine systems that are characterized by long periods of ice cover and short periods of open water when wave action and storm activity are important. Permafrost, sea ice and wind-wave conditions are driven by regional and local climate forcing and interact in such a way that a change in one produces feedbacks affecting the other two. Vast stretches of Arctic coastlines are undergoing unusually high rates of annual retreat and increased occurrence of a variety of mass wasting related landforms: block failures, retrogressive thaw slumps and active layer detachments (Harper, 1990; Jones et al. 2009). In comparison to Arctic coasts marine shorelines (with coastal cliffs) in more temperate regions experience on average between 0.1 and 10.0 m yr^{-1} of retreat depending on their lithology (Sunamura, 1992). Unlike Arctic coats which are ice free for only 2 months of the year temperate coasts experience little or no sea ice affects. Block failures, also termed as block slumping, are considered to be an important component of coastal and river bank retreat in permafrost regions with semi-cohesive fine-grained sediments (Lawson, 1983; Walker, 1988; Walker and Arnborg, 1963; Williams and Smith, 1989). Field observations (Fig. 1) indicate that mass wasting can occur almost year-round through the failure of large sediment blocks, for example large blocks of frozen sediment have

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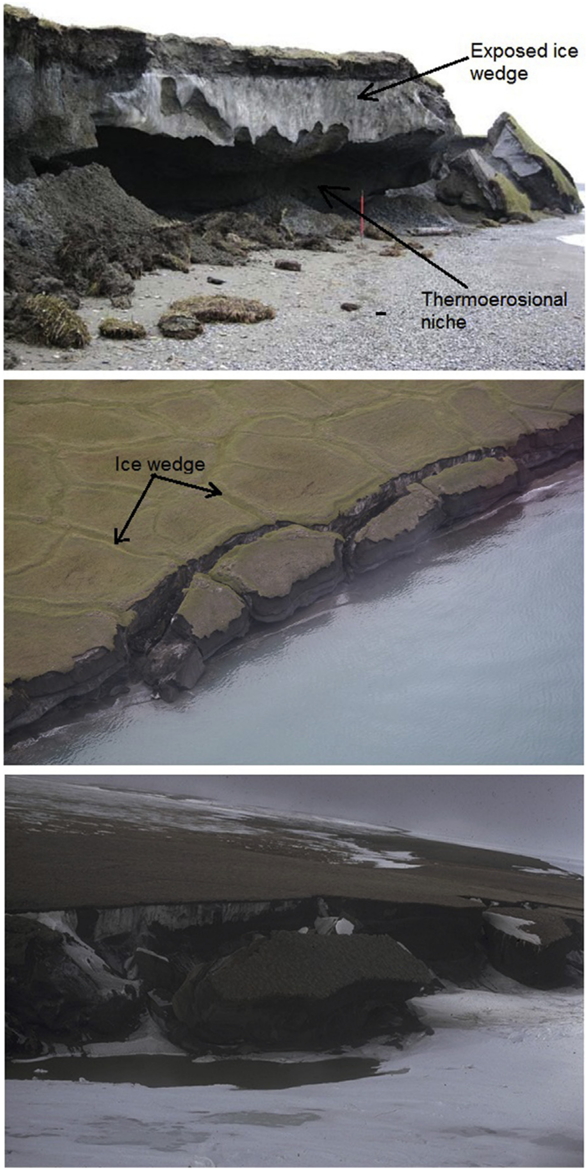

Fig. 1. These photos illustrate the range of block failures along the southern Beaufort Sea coast. The top photo shows a large thermoerosional niche undercutting a low (7 m) bluff. The middle photo shows the semi-continuous nature of block failures in some areas and the bottom photograph shows a large block (~13 m high) resting on the sea ice. In all three cases the failure occurred along the longitudinal axis of an ice wedge which is visible in the back wall.

been observed resting on the sea ice as well as in shallow water. The role of undercutting and the presence of massive ice and ice wedges are often cited as factors affecting block failure (Walker, 1988; Walker and Arnborg, 1963).

The terminology used to describe various erosion processes and landforms along Arctic coasts can be confusing due to the frequent use of different words derived from other languages to describe the same features. In this paper we use the terms *thermoerosional* when referring to wave-related erosion caused by the combined processes of melting permafrost and ground ice, and the mechanical removal of sediment particles by hydraulic processes, and *block failure* to describe the resulting mass wasting of large masses of ice-bonded sediment. The IPA Multi-language Glossary of Permafrost and Related Ground Ice Terms defines *thermoerosional niche* "as a recess at the base of a river bank or coastal bluff produced by thermal erosion of ice-bonded permafrost" (van Everdingen, 1998). Our use of the terms thermoerosion, block failure and thermoerosional niche are consistent with the North American permafrost and rock mechanics literature on these subjects.

There are numerous studies on Arctic coastal retreat focusing on the monitoring of shoreline changes and/or discussing different types of erosion processes (Brown et al., 2003; Jones et al., 2008, 2009; Lantuit and Pollard, 2005; Leont'yev, 2003; Leont'yev, 2004; Mars and Houseknecht, 2007; Novikov and Fedorova, 1989; Ogorodov, 2005; Shur et al., 2002; Solomon, 2003, 2005; Solomon and Coville, 1995). Modeling studies on Arctic coastal retreat are mostly focused on thermoerosional processes (Barnhart et al., 2014; Ravens et al., 2012; Kobayashi, 1985; Kobayashi and Virdrine, 1995; Kobayashi et al., 1999). These studies developed process based models describing the thermoerosional niche formation and thermoerosion of collapsed cliff materials. Ravens et al. (2012) suggest that when the thermoerosional niche exceeds an assumed critical depth (~10 m), the weight of the overhanging bluff exceeds its shear strength and the bluff suffers block collapse. Other erosion modeling studies in the region have dealt with sediment transport due to storm surges and wave action during the open water period (Hoque et al., 2009; Couture et al., 2008). In light of the expected changes in the length of the open water season and increased wave processes, the importance of thermoerosional processes along permafrost coasts cannot be under emphasized. For example, according to Aré (1988), the continental coasts of North America are mainly thermoerosional in nature. Similarly, Mackay (1963) states that the coast between Point Barrow and Langtton Bay is wholly thermoerosional. Lewellen (1970) also reported that the entire Beaufort Sea coast from Point Barrow to the Mackenzie Delta has undergone thermoerosion. Our long-term observations of permafrost processes and coastal erosion along the northern Yukon coast has found that the frequent occurrences of block failures following each major storm event support the hypothesis that thermoerosional processes are dominant along this coast. Based on our aerial and boat surveys of the Yukon coast, roughly 80% of the shoreline displays bluffs in which thermal erosion and block failures are common. However, the mechanics of block failure processes in the permafrost region are still poorly understood. This may partly be due to the complex nature of the failure process in frozen cliffs related to: (i) the existence of horizontal thermoerosional niches which undercut the cliff base and the lack of systematic data on niche geometry, (ii) the existence of ice-wedge polygons in the back slope areas affected by coastal erosion, and (iii) the complex strength and deformation behavior of frozen sediment due to the heterogeneous nature of ground ice conditions.

Most Arctic coastal landscapes underlain by continuous permafrost are characterized by ice-wedge polygons (French, 2007). In areas where ice wedges are present, block failure tends to occur along the longitudinal axis of an ice wedge oriented roughly parallel to the coast. For example, Aré (1988) reported that all the block collapse observed in August 1961 at Muostakh Island occurred along ice wedges. As illustrated in Fig. 1 collapsing blocks consists of a mass of frozen (ice-bonded) sediment within one or two polygons, surrounded on three sides by ice-wedge ices and exposed in the cliff behind the fallen block is an ice wedge in longitudinal section. These field observations led to our hypothesis that failure in this situation occurs when a thermoerosional niche reaches a critical depth such that the loss of underlying support increases shear stresses acting on the frozen soil mass immediately inland of the niche. When there is an ice wedge within the zone of increased stress the block will tend to fracture in the area of the most recent thermal contraction crack and then collapse is