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# Analysis of a sudden bluff failure along the southwest Lake Michigan shoreline

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ABSTRACT

Elevated lake levels in the Lake Michigan-Huron basin have resulted in erosion at the bases of coastal bluffs composed of unconsolidated glacial deposits. Base erosion leads to a general steepening of the bluff face that can cause the bluffs to suddenly fail, transporting sediment into the nearshore hydrodynamic system. Sudden bluff failure impacts infrastructure built near the bluffs and the sediment budget of the coastal region. A better understanding of the mechanics that govern bluff failure will improve predictions of bluff retreat and sediment budgets. Here we present findings collected from a set of newly developed in-situ monitoring devices that record and measure several properties of the bluff leading up to and during a sudden failure. The devices are capable of accurately measuring, amongst other properties, displacement of the failing bluff at the millisecond sampling rate needed to capture sudden changes. A bluff failure was recorded on December 13, 2016, which prior to failure underwent an elevated creep rate for approximately 1.5 days and a highly-accelerated creep rate for the final 2.5 h. A creep to failure technique was used to analyze the displacement record and substantiated that the bluff failure was likely caused by the formation of segregation ice within the bluff as temperatures dropped from −1 to −12 °C over a 40-hour period prior to failure. Finally, a time to failure prediction estimate provided an upper bound for the time until ultimate failure from any one instance of time depending on the instantaneous creep rate.



## Introduction

High lake levels in the Lake Michigan-Huron basin (Smith et al., 2016) are reducing beach width along the Lake Michigan coastline allowing wave action to erode the bases of coastal bluffs at the highest rate of the past 30 years. As much as 70% of the Lake Michigan shoreline in Wisconsin consists of bluffs that are composed of unconsolidated glacial deposits (Mickelson et al., 1977; Chapman et al., 1997) and are susceptible to erosion (Mickelson et al., 2004). As the bases of bluffs are eroded they become steeper and ultimately fail (Brown et al., 2005; Swenson et al., 2006; Edil, 1992, 2013), mobilizing sediment downslope into the nearshore hydrodynamic system. The impacts of bluff failure on society are two-fold; 1) infrastructure that is built atop or near the bluff edge is at risk of destruction, 2) elevated flux of bluff sediment into the coastal environment affects beach stability, aquaculture habitat, waterway and harbor maintenance cost, and coastal infrastructure protection. The impacts of bluff failure to structures, and the contributions of bluff sediment to the nearshore sediment budget, has been recognized in southeast Wisconsin since at least the 1840s (Lapham, 1847), but recent bluff erosion, exacerbated by high lake levels, has increased interest in relocating or demolishing facilities because of financial liability and protection of human safety. A better understanding of the mechanics of bluff failure will lead to improved predictions of bluff stability, which can aid county parks managers, coastal managers, and private citizens in assessing the long-term stability of shoreline behavior. Bluffs that readily fail will act as “feeder” bluffs whose sediment supply can replenish down-coast beaches, while bluffs that have long-term stability will not contribute as much sediment supply to the nearshore hydrodynamic system for beach building processes (Montgomery, 1998).

Bluff sediments released though landslides significantly contribute to the coastal sediment budget. Sediment budgets for Lake Michigan have estimated that half the sand-sized particles eroded from bluffs are deposited into deep lake basins while the other half remains in nearshore sand bodies, beaches, and dunes (Colman and Foster, 1994). Notably, sediment budget calculations have also shown that sediment liberated through bluff erosion is the dominant source for the sand-sized particles that comprise the beaches of Lake Michigan (Colman and Foster, 1994). Other researchers have found that the leading cause of bluff erosion is shallow to intermediate depth translational landslides (Jibson et al., 1994). Therefore, a well-developed understanding of the mechanisms that lead to shallow to intermediate landslide failure is necessary for accurately estimating sediment budgets.

Bluff failure is an inherently irregular process that occurs rapidly once static forces are imbalanced (Edil, 1992; Chase et al., 2001;

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Mickelson et al., 2004). The mechanical processes that lead to bluff failure once the slope is near a static force imbalance, and the factors that can drive a bluff close to a force imbalance to failure, are not well understood. We have developed and deployed a network of in-situ sensing devices along the bluffs of Lake Michigan to better understand the timing and character of failure mechanics active within the bluffs.

## Study area

The study area is located in southeastern Wisconsin and consisted of two sites (Fig. 1). Site one is located in the Village of Mt. Pleasant, Racine County, where bluffs are typically 10 m high. Site two is located near the town of Port Washington, Ozaukee County, at the site of Clay Bluffs/ Cedar Gorge Nature Preserve with bluffs that are approximately 30–45 m high. The stratigraphy along the Lake Michigan shoreline in Wisconsin is well documented (Mickelson et al., 1977); and, in general, bluffs are composed of sandy nearshore and outwash sediment interbedded with clay rich till deposited near the end of the late Wisconsin (MIS 2) glaciation. In many places till is in direct contact with wave erosion along the shoreline, although some sandy strata are present in nearly all exposures. At site one sand occurs at the surface, is approximately 6 m thick, and overlies till that is exposed near the bluff base. Site two is composed primarily of two tills separated by 1–2 m of sand.

## Methods

We have developed and deployed in-situ bluff movement monitoring devices. Three devices were deployed as shown in Fig. 1; two at site one (CM1&2), and one at site two (CM3). The devices were active from mid-August to late December of 2016. Details about the devices, deployment and methods used to analyze the results are detailed below.

### *Device*

The objective of this study was to capture and record both effects of failure and site conditions that could drive bluff failure; therefore, the devices are capable of recording data at a millisecond sample rate with 24-bit precision. These devices, named the Bluff Assessment Data

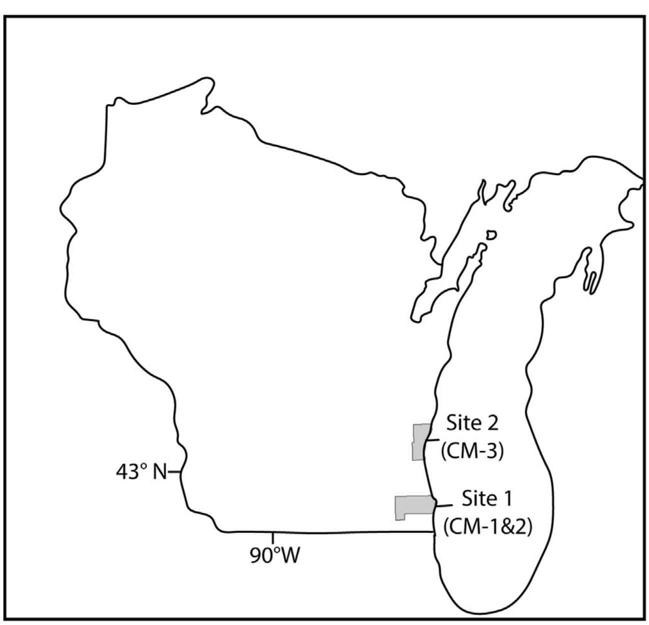


**Fig. 1.** Location of study sites along the southwestern Lake Michigan shoreline. Racine and Ozaukee Counties in Wisconsin are shown in gray. The locations of devices CM1, CM2, and CM3 are listed by the site location.

Generating Experiment Recorders (BADGER), were capable of recording the following metrics: GPS-L1 position and time, soil moisture, soil temperature, atmospheric humidity, atmospheric temperature, and displacement using two spool-style extensometers with ca. 20-micron resolution over a range of 0–3000 mm at a sub-second sample interval. The extensometers were used to measure relative movement between three points on a hillslope as it underwent creep. All data were digitized with a 24-bit precision digitizer and written to an onboard SD card. The sample rate can vary in response to rate of change of the various measured factors, but has a maximum sampling rate of 10 Hz. The GPS was also used to generate a time record that is accurate to within one millisecond. This level of timing precision allows for cross-comparison of data recorded on multiple BADGER devices if desired. The dual spool-style extensometers were extended at right angles to one other so the direction and magnitude of slip could be calculated. The devices are powered by one 35 Ah deep-cycle battery. The low power draw (0.4 W) of the BADGERs allowed them to run on one battery for a minimum of 30 days without need for charging. Extensometers have been used to measure gulley erosion (Thomas et al., 2004) and bluff motion in the past (Chase et al., 2001; Kaunda et al., 2008; Glynn et al., 2012), but not at millisecond sampling rates.

### *Deployment*

Site selection for the BADGERs was an important aspect for their success and survival. Sites were identified where bluff failure was possible in the near future. These locales were identified through two criteria known to correlate with imminent failures; 1) an over-steepened bluff toe that places the bluff's static state close to a force imbalance, 2) a surface crack paralleling the bluff face along the top of bluff indicating some amount of creep. A surface crack was not always present prior to sudden failure, but the presence of a crack provided a method to identify an area of relative stability and an area that was likely to fail. Instrumentation (each BADGER device includes a digitizer, battery, soil probe, and spool-style extensometer) was installed in places on each bluff least likely to be destroyed in the event of a large failure. Once a suitable site was located, the digitizer, battery, soil probe, and spool-style extensometers were placed on the "stable" portion of the bluff. A hole was augured into the bluff surface ~20 cm deep ~1 m from the digitizer, the soil probe was inserted and the hole backfilled. The extensometers were placed atop 1.5 m length composite wood and steel stakes that were hammered into the bluff top (Fig. 2). The cable was then partially drawn out of the extensometer and staked at ground level to the portion of the bluff top that was expected to fail. The extensometer consists of a steel cable that unspooled as displacement occurred. The placement of the extensometer spools 1.5 m above ground surface decreased the chance of interference by plants and animals, and in the event of bluff motion provided an angle for the cable to extend without interfering with the growing bluff edge. In an effort to provide a "weak link" in line with the steel cable to prevent it from snapping in the event of a sudden failure, a ~10 cm section of monofilament line was inserted between the end of the steel cable and the stake at ground level. The digitizer and battery were wrapped in a plastic tarp to shield them from the elements (Fig. 2).

### *Creep-to-failure*

We utilize the creep to failure technique to analyze high temporal resolution time series creep records in an effort to constrain the mechanical factors that lead to sudden bluff failure. The creep to failure technique utilizes the rapidly sampled continuous displacement record leading up to and during a sudden failure to evaluate the internal mechanics that govern the failure process (Voight, 1989; Main, 1999). The method was first used to describe the failure of geologic materials and metals through the linking of microcracks and vacancies (Voight,