Journal of Great Lakes Research 40 (2014) 102–114

Contents lists available at ScienceDirect

Journal of Great Lakes Research

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

A field study of nearshore environmental changes in response to newly-built coastal structures in Lake Michigan

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ARTICLE INFO

Article history:
Received 24 July 2013
Accepted 20 December 2013
Available online 25 January 2014

Communicated by: Harvey Thorleifson

Keywords:
Coastal structures
Cohesive coastal bluffs
Lakebed downcutting
Integrated geophysical techniques
Equilibrium beach profiles
Sediment budget

ABSTRACT

In this study, we monitored changes of cohesive nearshore environment including bluff and lake bottom/bed response to newly-built coastal structures with a thousand-meter-long revetment in Lake Michigan shoreline over a six-year study period. Sequential aerial photos showed that excessive slumping occurred only on the south bluffs and no bluff recession in the middle areas with coastal structures. Field measurements using our recently developed integrated geophysical techniques provided information on bathymetry, sand layer thickness, and lakebed downcutting over the nearshore reach of Concordia University in Lake Michigan. During the study period, the bathymetry profiles at the study site fluctuated dynamically, especially in the regions outside the shoreline structures, suggesting continuous and ongoing sediment erosion and deposition. The lakebed downcutting in front of the newly-built coastal structures is correlated with CWIH (cumulative wave impact height). Significant differences of lakebed downcutting in the north and south natural beach regions were revealed and may be associated with the nearshore sediment budget. The southwardly dominant longshore current maintains the equilibrium state of beach profiles in the north region, but the coastal structures prevent sediment supply from the well-protected bluffs in the middle region to the south region. The possible source of sediment supply in the south region is therefore from lakebed or bluff materials, supported by excessive bluff failures and lakebed downcutting. Overall the newly-built coastal structures seem to pose negative impacts on bluff stability at the south shore of the coastal structures.

Introduction

The nearshore environment, located at the interface between the terrestrial landscape and open-water, plays an important role on ecosystem functions in the Great Lakes (Meadows et al., 2005). The nearshore environment is susceptible to hydrodynamic forces such as waves, currents, and water level fluctuations (Amin, 1991; Brown et al., 2005) as well as coastal protection structures such as breakwaters, jetties, groins, and harbors (USACE, 2002). Physical features of the nearshore environment such as bathymetry and sediment properties (composition, porosity and top-layer thickness) can affect habitats and biological communities (Goforth and Carman, 2005; Mackey and Liebenthal, 2005). For instance, bathymetry affects nearshore wave climate and circulation patterns, which in turn transport bottom sediments and redistribute biota (Chapelle et al., 2000). Sediment substrata, *e.g.* composition and porosity, are associated with species of fish and benthic macroinvertebrates (Hayes et al., 2009; Robillard and Marsden, 2001). The balance of sediment budget in the nearshore environment can determine the stability of coastal bluffs, which can cause great concern for the safety of human lives and properties (Heinz Center, 2000).

Coastal structures are commonly used to stabilize shorelines, especially steeper bluffs, to prevent further bluff erosion or slumping to nearshore environment (US Army Corp of Engineers, USACE, 2002). To date the effects of the coastal structures on beach profiles are still controversial. Many studies (Kraus, 1988; Kraus and McDougal, 1996; Plant and Griggs, 1992) found that beach profiles were not significantly affected by the presence of the coastal structures. On the contrary, Miles et al. (2001) showed that the "hard" coastal structures can cause larger waves due to reflection and in turn induce additional sediment resuspension and transport, leading to excessive nearshore bottom erosion (Dean, 1987; Lee and Ryu, 2008). Komar and McDougal (1988) suggested that beaches adjacent to the coastal structures could experience excessive erosion which is the so-called end-of-wall effect (Basco, 2006; Dean, 1987). Possible mechanisms for the end-of-wall effect can be due to sand trapping (Dean, 1987), blockage of littoral drift (Griggs and Tait, 1988) or rip currents and seaward return flows (McDougal et al., 1987). Furthermore, apparent morphological changes can be observed at spatial scales exceeding the structure dimension due to the disturbance of the shore-parallel net sediment flux (Kraus and McDougal, 1996). The interruption of longshore sediment movements by coastal structures may result in down-drift shoreline erosion over hundreds of meters or kilometers, affecting bluff stability and accelerating bluff recession rates to considerable distances from the structures (Dean and Dalrymple, 2002). While we

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http://dx.doi.org/10.1016/j.jglr.2013.12.013

have gained a good understanding on the role of coastal structures in eroding lake-bottom along non-cohesive nearshore environments, very few studies have documented the elevated cohesive lakebed erosion (also called downcutting) which is one of the important factors determining the long-term bluff recession rate in the Great Lakes (Kamphuis, 1986).

Difficulties in measuring lakebed downcutting and thickness of overlying sand are recognized. The thickness of the sandy layer plays an important role in lakebed downcutting (Davidson-Arnott and Ollerhead, 1995). A thick sandy layer can protect the lakebed from being eroded, while a thin sandy layer can promote lakebed downcutting because of sandy particle abrasion (USACE, 2002). Traditionally a micro erosion meter (MEM) installed and operated by divers was employed to measure the lakebed elevation and sandy layer thickness (Davidson-Arnott and Langham, 2000; Davidson-Arnott and Ollerhead, 1995). However, intensive logistic efforts limit the number of samplings taken, which may not be adequate to define spatial variations of downcutting over substantial areas (Davidson-Arnott and Langham, 2000). In addition, disturbances of MEM on sediment properties can occur during installation and data collecting by divers. Therefore, efficient and accurate monitoring techniques on the changes of large-scale nearshore environment are highly desired.

Recent advancement of geophysical techniques has enabled repeatable survey of lake-bottom (bathymetry) and sediment substrata (Bradford et al., 2005; Cagatay et al., 2003). Generally, two geophysical techniques have been successfully applied to the nearshore area mapping. First, acoustic wave-based techniques are based upon changes of mechanical impedance, which is related to the product of acoustic speed and the density of the medium (Lin et al., 2009). Second, techniques based upon electromagnetic (EM) waves measure reflections created at interfaces with contrasting dielectric permittivities (Annan, 2005). In principle, acoustic and EM signals can reflect any abrupt changes of physical properties at the interface of different mediums (water–sediment, or sand layer-clay layer). Water depths and sediment layer structures thereby can be estimated and delineated. Nevertheless, the two techniques have their individual limitations. Acoustic signals have difficulty in penetrating through coarse-grained sediments (*e.g.*, sand and gravel) and glacial till due to low energy transmission and signal scattering (Morang et al., 1997). EM signal strength attenuates rapidly in high conductivity materials and penetrates only a few centimeters in clay cohesive sediments and sea water (Annan, 2005). However, by combining acoustic and EM signals, survey results may be able to depict and identify sediment properties with various particle sizes on lake floors.

In Lake Michigan, sediment compositions of nearshore environment are extremely diverse. Types of bottom sediments consist of cohesive clay, silt, sand, gravel, cobble, boulder, and bed rock (Brown et al., 2005; Waples et al., 2005). In the past, most studies obtained sediment porosity or layer thickness using either acoustic or EM techniques (Richardson and Briggs, 1993; Topp et al., 1980), depending on the prior knowledge of sediment types at the study sites. Difficulties in mapping a mixed type of sediment properties have been recognized (Morang et al., 1997). Recently Lin et al. (2009) developed a combined acoustic and electromagnetic technique to effectively monitor the diverse types of nearshore bathymetry and bottom substrata in Lakes Michigan and Superior. Employing an iterative inversion algorithm to integrate acoustic and electromagnetic geophysical measurements, porosities and top-layer thickness in sediments can be estimated with the errors less than 10% for each survey (Lin et al., 2010). While this integrated acoustic and electromagnetic technique is promising, no results on monitoring the change of nearshore sediment properties, in particular lake bed downcutting in front of near-built coastal structures, have been reported yet, to the best of the authors' knowledge.

The objectives of this paper are two-fold. Firstly, using the integrated geophysical instrument, we document the nearshore lake-bed and lake-bottom changes before and after installation of coastal structures built in Lake Michigan over a six-year study period (2007 to 2012). Based upon the subaerial and subaqueous observations, the differences of lakebed downcutting, and bluff stability and recession in the south and north shores adjacent to the newly built coastal structures in Lake Michigan are revealed. Secondly, we examine the effect of newly built coastal structures on the adjoining coastal bluffs and nearshore regions, especially cohesive bluff stability and lakebed vertical lowering (downcutting). Several physical drivers, such as water levels, cumulative wave impact height (CWIH), and longshore currents, are examined to discuss their effects on local differences of lakebed downcutting and bluff stability in the study site. The information should be valuable for future coastal development and management in the Great Lakes.

Methods

Study site

The study site, including subaerial and subaqueous parts, is located in Mequon, southern Ozaukee County, Wisconsin (Fig. 1). In the subaerial part, there are 45 m high bluffs extending 1.6 km along the shoreline of Lake Michigan, which included the Concordia University Wisconsin (CUW) sites on the bluffs. The bluff materials consist of clay, ripple-marked sand, cobble, and boulder. The foreshore material is mainly sand (Brown et al., 2005). The underlying glacial till is primarily composed of fine lacustrine deposits (only 10–25% sediments coarser than 0.1 mm) susceptible to lakebed downcutting, a common process along cohesive coastal bluffs in the Great Lakes (Davidson-Arnott and Ollerhead, 1995). Based upon the analysis of aerial photographs (Brown et al., 2005), before 1995 the bluff recession rate for the crest and the toe was 0.36 to 2.19 m/year and 0.32 to 0.77 m/year, respectively, depending on water levels in Lake Michigan. To mitigate continuous bluff slumping hazards, a bluff stabilization project was undertaken in 2005. The coastal structures including revetment and rubble mounts intended to protect the bluff toe erosion on the CUW campus were constructed and completed in 2008. Coastal revetments were also constructed on several private land owners at the bluff toes, south of the campus (Fig. 1). For the subaqueous part, we focus on the areas with water depth less than 3 m at which depth wave breaking often occurs.

Bluff recession rates

Following the method developed by Hatch (2004) and Swanson et al. (2006), we obtained recession rates of bluff crest and toe by using sequential aerial photographs. Three different years (*i.e.*, 2000, 2005, and 2010) of aerial photos were digitized and processed to create geo-referenced orthophotos with the resolutions of 1 m/pixel. The accuracy of the bluff crest and toe location is approximately ± 1–2 m, based upon a sampling interval of 10 m transect over an approximately 2000 m shoreline (1000 m for the main CUW and ± 500 m northern and southern sides of the CUW, Fig. 2). The issues of trees on the bluff top and high reflectance of some air photos can affect the visibility of the bluff description. According to Hatch's suggestions (2004), we employed histogram stretch enhancements to improve image quality. By averaging the locations of the bluff crest and toe for the north, middle (CUW), and south sides, the accuracy was improved to 0.09 m.

Integrated geophysical techniques and ground-truth measurements

To map nearshore bathymetry and substrata, combined geophysical techniques (Lin et al., 2009) including a sub-bottom profiler (SBP) and a ground penetrating radar (GPR) system in a zodiac boat were employed (Fig. 3). The SeaKing parametric SBP, manufactured by Tritech International Limited, emits two different signals (around 100 kHz) to create high (200 kHz) and low frequency (20 kHz)