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CFD Modeling of Arctic Coastal Erosion due to Breaking Waves

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Computational fluid dynamics (CFD) modeling of breaking waves over a slope and the resulting erosion in the case of an Arctic coastline is presented in this study. The study is performed with the open-source numerical model REEF3D. First, the numerical model is validated for the simulation of incident waves, wave breaking on a slope, and the sediment transport process. The numerical results show good agreement with wave theory and experimental data. The validated numerical model for the hydrodynamics and the sediment transport process is then used to simulate the coastal erosion process under the breaking wave impact on a vertical bluff. An Arctic coastline at Bjørndalen region at Isfjorden, Svalbard, is chosen, where a significant coastal erosion was observed during a storm event in September 2015.

INTRODUCTION

Most of the Arctic coastline is susceptible to climate change. Because of global warming and the transfer of additional heat fluxes, the frozen period of the upper active layers in the Arctic coastline is reduced. Consequently, coastline stability decreases during the extended warmer period. The average thickness of the active sediment layer in Svalbard, Norway, varies between 1.0 and 10.0 m and consists of coarse-grained sandy soil (Fromreide, 2014). Climate change can affect this Arctic coastline in two ways. First, the extended warmer period results in the formation of deeper and weaker active sediment layers (IPCC, 2007). Second, the melting of the Arctic ice sheets increases the sea level, resulting in higher tides. In combination, the higher tides approach the Arctic coastline (Thompson et al., 2016) and erode the weaker active sediment layer. A recent example of this change has been experienced in the Bjørndalen region in Isfjorden, Svalbard, where significant coastal erosion occurred during a storm event in September 2015. The waves reached the cabins built near Isfjorden and resulted in an almost 1.0-m-deep scour hole (Barstein, 2015). Therefore, in order to better understand the coastal erosion phenomenon in the Arctic regions, the processes of wave breaking and the resulting sediment transport have to be investigated in detail. The study is also important for the design of new coastal structures and suitable mitigation measures at the Arctic coastline.

The physical process of erosion at the coastline is defined as follows: wave breaking near the bed results in higher bed shear stresses around the breaking point. An increase in the bed shear stress compared to the critical shear stress initiates sediment pickup, and wave-induced currents transport sediment away (Sumer et al., 2002). Further, if the bluff or a seawall obstructs the coastline, the wave impact creates an undertow current. It mobilizes the sediments from the toe, which are then carried offshore by the near-bed current. The process continues until the scour hole at the toe is deep enough to dissipate the wave impact (Fredsøe and Deigaard, 1992).

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KEY WORDS: Wave breaking, coastal erosion, free surface, breaking wave, seawall, Arctic coastline, large-scale CFD, REEF3D.

Coastal erosion has always been seen as an important factor of the stability of the coastline and has received considerable attention in works of the past decade, such as Chesnutt and Schiller (1971), Barnett (1987), Dean (1987), Hughes and Fowler (1990), Kamphuis et al. (1992), and Fowler (1992). In these studies, the cross-shore coastal erosion, the wave-induced erosion at the seawall, the beach reconstruction process under regular and irregular waves, the seawall scour for a three-dimensional movable bed under the oblique random waves generated on a sloping profile, and the change in beach profile for different wave heights have been discussed. The maximum scour depth at the seawall toe is seen to be less than or equal to the incident wave height. Kraus and Smith (1994) investigated long-shore and cross-shore sediment transport, seawall toe erosion, and seawall failure cases under severe storm conditions. It was found that the presence of a seawall majorly affects the immediate beach profile. However, the major part of the beach profile remains unaffected. Kraus and McDougal (1996) and Shimizu and Ikeno (1996) have studied the cross-shore sediment transport and the beach reconstruction process under regular and irregular waves. Among the recent studies, Sutherland et al. (2006) studied coastline erosion under the presence of a seawall. It is concluded that the maximum scour depth depends on the relative water depth at the seawall toe and wave similarity parameter (ξ_0). The seawall erosion is found to be insensitive to the slope of the seawall. Tsai et al. (2009) investigated the experimental results of the toe scour on a steep bed under breaking waves and found that the depth of toe scour increases with the steepness of the incoming wave. However, these studies focus on the sediment transport process under waves without a significant discussion about the wave hydrodynamics, which govern the erosion. This shortcoming is recognized, and experiments and numerical studies have been conducted to investigate the breaking wave hydrodynamics in the surf zone, the turbulent flow field, and the wave breakers by several researchers, e.g., Nadaoka and Yagi (1990), Ting and Kirby (1995), Stansby and Feng (2005), Christensen (2006), Lubin et al. (2011), and Makris et al. (2016).

The development of a numerical model for sediment transport due to wave action is a challenging task, and only limited progress has been made in this area: e.g., Bihs and Olsen (2011), Ahmad et al. (2015, 2016, 2018), and Afzal et al. (2015). In these studies, flow hydrodynamics around coastal structures such as piles, pipelines, and abutments is obtained by solving the Navier–Stokes