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Short Communication

Stability analysis of waterfall cliff face at Niagara Falls: An implication to erosional mechanism of waterfall

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ABSTRACT

Although recession of waterfalls or knickpoints in bedrock rivers is a common geomorphological process, detailed mechanics of waterfall recession has only been examined in a few cases. Caprock recession model at Niagara Falls, in which gravitational collapse of caprock induced by undercutting notch plays a significant role, has been one of the well-known models describing the waterfall erosion, but the validity of the model has hardly been examined in a quantitative context. Here we assess the stability of the cliff of waterfall face of Niagara Falls in terms of the strength of bedrock and the length of undercutting notch. The result of a cantilever model analysis shows that the caprock remains stable until the undercut reaches tens to over a hundred meters. However, the actual length of undercutting notch of waterfall face is up to 10 m, and such a long notch to cause gravitational collapse of the caprock can hardly be formed. The recession of the waterfall could therefore be caused by gradual detachment of the rock of the waterfall face induced by fluvial erosion of surface water flow, rather than by elongation of undercutting notch and episodic gravitational collapses of the caprock.

1. Introduction

Fluvial erosion is a significant agent in shaping bedrock landforms in mountains and hills (Wohl, 1998), and the erosion is often active and intense at waterfall sites (Begin et al., 1980; Young, 1985). Rates of bedrock erosion at waterfalls are abruptly higher than those in the other portions of riverbeds (Young and Wray, 2000; Hayakawa and Matsukura, 2002), and the rapid erosion at waterfalls often causes upstream propagation of incision and rejuvenation of longitudinal profile of streams (Howard et al., 1994; Whipple et al., 2000; Schlunegger and Schneider, 2005; Hayakawa et al., 2009). However, despite the significance of waterfall in bedrock river morphology, mechanisms of erosion at waterfalls remains uncertain: Although some studies have emphasized on research needs for erosional mechanism or processes of waterfalls (e.g., von Engeln, 1940; Young, 1985), only a limited number of studies have previously examined this issue (e.g., Bishop and Goldrick, 1992; Frankel et al., 2007; Lamb et al., 2007, 2008; Lamb and Dietrich, 2009). Since a well-known undercut model for the mechanism of waterfall recession has been proposed by Gilbert (1890) at Niagara Falls in northeastern North America (Figs. 1 and 2A), whose argument is that the recession of Niagara Falls occurs by undercut erosion of the lower shale layer at the waterfall face followed by the collapse of the upper dolomite layer, this undercut model, also referred to as the caprock model, has long been the most famous and commonly cited as the representative erosion model of waterfalls. However, Gilbert's (1890) argument has just been based on a qualitative description that the overhanging upper dolomite layer seems harder and the underlying lower shale layer seems to be weak enough to be easily eroded, and quantitative support for the model has been limited. As far as the authors know, there has been no significant progress in researches on the mechanisms of erosion at Niagara Falls since the Gilbert's (1890) argument, with some exception by Tinkler (1994, 2004) who suggests that the plunge-pool current or swirling flow seems to have insufficient power to erode bedrock at the base of the waterfall, and by Philbrick (1970) who emphasizes the stress release as a dominant factor for the progressive collapse of the waterfall face. Although Barlow (2002) has pointed out the failure of east-facing cliffs along the Niagara Escarpment, west of Lake Ontario, occurs by the sliding of the upper dolomite caprock according with the slow plastic deformation of underlying shale layer, this type of deformation can only occur in weathered rocks along the cliff without erosion by stream water, so that this may not be applicable to the waterfall face where fresh bedrock always exposes.

To test the validity of the undercut erosion hypothesis of the waterfall, i.e., the possibility of collapse of the overlaying caprock dolomite layer by undercut of the lower shale layer, here we perform a quantitative assessment of mechanical properties of the rock at Niagara Falls and the stability of the cliff of the waterfall face. First, for the assessment of the rock strength, we use a Schmidt hammer equipment to obtain the unconfined compressive strength of the rock

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Fig. 1. (A) Map showing Niagara Falls (Horseshoe and American Falls) and locations where Schmidt hammer measurements are undertaken along the Niagara River. (B) Overview photograph of Niagara (Horseshoe) Falls taken on March 2009. Location of the notch shown in Fig. 2C is shown.

mass including some effects of surface discontinuities with centimeter-scale spacing. Then we test a cantilever beam model using the rock strength data to examine the stability of the waterfall face with long undercut notch. This simple model of cliff failure is a prevailing theory but has never been tested for the case of waterfall erosion.

2. Overview of Niagara Falls

Niagara Falls was formed approximately 12,500 y BP at the north-facing cliff of the Niagara Escarpment between Lake Erie and Lake Ontario, when the Niagara River started draining over the escarpment after the disappearance of the Laurentide Ice Sheet in the region (Tinkler et al., 1994). Since then, the waterfall has receded for ca. 11 km at an average recession rate of 1 m y^{-1}, leaving a deep, box-shaped valley named Great Gorge downstream of the waterfall (Lewis and Anderson, 1989). Currently Niagara Falls comprise two major falls, Horseshoe Falls and American Falls. Horseshoe Falls is the main drop of Niagara Falls, over which 90% of water discharge in the Niagara River flows, having a lip length of 762 m and a height of 51 m. The surrounding area of Niagara Falls is well maintained as National Park, where many roads are located on the edge of cliffs along the Niagara River, and sightseeing trails and tunnels are constructed below and inside of the cliffs.

Previous studies on the recession of Niagara Falls have mostly focused on this Horseshoe Falls whose recession history has well been recorded, providing detailed descriptions regarding its recession through the last century (Gilbert, 1907; Philbrick, 1970; Tinkler, 1987). The caprock erosion model of waterfall was derived from this Horseshoe Falls (Gilbert, 1890, 1907). In contrast, American Falls, the sub-drop of Niagara Falls with a 335-m long lip and a 54-m height, has a vertical face but never been undercut, at least since the Gilbert's observation in the late 19th century, due to the accumulated rock blocks at the bottom of the waterfall face like a talus slope. It would be possible that American Falls had also been undercut in the past, especially at the early stage of its formation just after the passage of the main drop of Niagara Falls, but the insufficient water discharge through the American Falls side (10% of the total discharge of the Niagara River) should have prevented to remove the blocks below the waterfall face, and the undercut has been immediately obscured. Nonetheless, American Falls has also receded with a rate of 0.1 m y^{-1} for the past 500 years (Gilbert, 1907).

Some slope failures have been historically observed in the cliffs around the waterfall. A collapse at the Prospect Point on the right-side bank of American Falls, whose cliff face was not undercut but buttressed, occurred in 1954, but this did not affect the shape of the waterfall itself (Dunn, 1998). Also, the Table Rock, an overhang of cliff top on the left side of Horseshoe Falls, is known to be collapsed in 1850. However, although such rockfalls of the overhanging upper dolomite and resultant block accumulations beneath the cliff have often been observed in the sidewalls of Horseshoe and American Falls, the collapse of the lip of the waterfalls under water streams have hardly been reported.

The substrate rock along the Niagara River consists of alternating layers of dolomite and shale, slightly dipping southward. At the present position of Niagara Falls, the upper layer is the Lockport dolomite with a height of 30 m, and the lower layer is mostly the