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.

Keywords: waterfall; cliff stability; rock strength; erosional process

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, 1942; 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 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

Fig. 1 & Fig. 2 near here

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 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 yBP 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 Rochester shale with a height of 21 m (Fig. 2B). Although Gilbert (1890) speculated that the depth of the plunge pool is deeper than 60 m (Fig. 2A), accurate dimensions of the under-water morphology has not been measured (Fig. 2B). On the cliff face at and around Horseshoe Falls, the upper dolomite layer is hanging over the lower shale layer. The horizontal length of the notch undercutting into the shale layer, here referred to as the notch length, is several meters and no longer than 10 m (Fig. 2C). There is a window on the waterfall face from a tunnel within the shale layer for sightseeing, named "Journey Behind the Falls", is another evidence for the short notch length.

3. Rock strength measurement

3.1. Method

Schmidt hammer (N-type) is used to quantify the bedrock strength of the dolomite and shale layers at the present position of Niagara Falls and riverside cliffs along the Niagara River. To obtain the rebound values, R_N (%) showing the intact mass strength of the rock, the repeated impact method which involves 20-times impacts at each point is applied (Hucka, 1965; Matsukura and Tanaka, 2000; Matsukura and Aoki, 2004). The position of the Schmidt hammer measurement is set at several points for both the dolomite and shale layers around the waterfall, mostly on the wall of the Great Gorge. Both fresh and weathered bedrocks under wet condition are measured for each rock type. Although fresh bedrock of the lower shale layers is hardly found on the Great Gorge walls, an outcrop of shale was found at a road-side wall in the Canadian side. The Schmidt hammer measurements are also carried out in several locations along the Great Gorge downstream, whose rock surface is commonly weathered.

Bedding planes are apparently much denser in the shale layers than in the dolomite layer. The spacing of bedding planes in the shale layer is commonly as small as several centimeters. The obtained Schmidt hammer rebound values can therefore, especially as the result of the repeated impact method which gives mass strength (Matsukura and Aoki, 2004), moderately reflect the effect of the dense bedding planes which may reduce rock mass strength.

The R_N values are then converted to the unconfined compressive strength S_c (MPa) using a standard conversion equation attached with the Schmidt hammer equipment (log (S_c/0.098) = 0.0307 R_N+1.4016). The tensile strength S_t is then estimated from the compressive strength S_c using a general value of britness, the ratio of S_t to S_c, which ranges from 5 to 25 for various rock types (Sunamura, 1992).

3.2. Results

Although the measured Schmidt hammer rebound values by the repeated impact method does not show considerable difference between dolomite and shale if the weathering condition is the same, differences by weathering conditions were much clearer than those by rock types (Fig. 3, Table 1). Because the bedrock suffering from erosion under flowing water is usually fresh, we adopt the average rebound value for fresh dolomite and shale (R_N = 52.3%) as the representative value of the rock mass strength. This is equivalent to the S_c of 99.71 MPa, which is quite similar to the S_c for the dolomite layer along the Niagara Escarpment near the Niagara (99.75 MPa) reported by Barlow (2002).

Fig. 3 & Table 1 near here

4. Cantilever beam model for stability analysis

4.1. Model

When assessing the stability of cliffs with undercutting notches, the cantilever beam model, which enables to estimate critical notch depth, is often suitable for the assessment (Timoshenko and Gere, 1978; Thorne and Tovey, 1981; Abam, 1997; Matsukura, 1988; Kogure et al., 2006). The cantilever beam model approximates the stress distribution inside an undercut cliff with rotational moment (Fig. 4). In this model, the maximum bending stress $\sigma_{\max}$ inside a cliff is given as:

$$\sigma_{\max} = \frac{M}{Z} \qquad (1)$$

where M is the bending moment and Z is the modulus of the section. At a given width (b) and height of a cliff (h), M and Z are expressed as:

$$M = \frac{1}{2}\gamma b h l^2 \qquad (2)$$

$$Z = \frac{1}{6} b h^2 \qquad (3)$$

where l is notch length, γ is unit weight of the material comprising the cliff. Because the compressive strength of rock (S_c) operating on the upper section of a cliff is generally 5–25 times greater than the tensile strength (S_t) (e.g., Sunamura, 1992), the tensile strength is predominantly responsible for the cliff failure (Fig. 4). Since the cliff failure is supposed to occur from the upper section when the maximum bending stress $\sigma_{\max}$ exceeds the tensile strength S_t, the critical notch length l_c is obtained from Eqs. 1, 2 and 3 by replacing $\sigma_{\max}$ with S_t and l with l_c as:

$$l_c = \sqrt{\frac{hS_t}{3\gamma}} \qquad (4)$$

4.2. Analysis

The stability of the waterfall cliff is computed with some different parameters in terms of the rock strength. First, to quantify the stability of the upper dolomite layer at the face of Horseshoe Falls, the relevant parameters of a typical case are substituted into Eq. 4 as follows: h, the height of the dolomite layer, is 30 m; S_t is 3.99–19.9 MPa; γ is 0.025 MN/m^3 to which the mean γ value of the Amabel formation (dolomite) in the Niagara Escarpment is applied (Barlow, 2002). The critical length of undercutting notch (l_c) is then expected to be 39.6–88.5 m.

As a minimum estimate of rock strength of the fresh dolomite, the minimum R_N for the fresh dolomite (41.4%; Fig. 3) gives 1.85–9.23 MPa of S_t, and the critical notch length l_c is estimated to be 26.9–60.2 m. If the minimum R_N for the weathered dolomite (23.0%) is adopted, the critical notch length l_c is computed to be 14.1–31.4 m.

The size effect on the rock strength may also occur, because internal joints and tension cracks within the dolomite can reduce the rock mass strength. Because Schmidt hammer rebound values reflect the strength of rock specimen size approximately a cube of side length 17.5 cm (Brook, 1993, p. 55), and the position of Schmidt hammer test is recommended to be at least 6 cm apart from visible joints (Day and Goudie, 1977; Gardiner and Dackombe, 1983; Aoki and Matsukura, 2004), it is supposed that the Schmidt hammer rebound value R_N (52.3%) for the fresh dolomite approximates the strength equivalent to small specimen at ca. 10 cm diameter. Since the strength of larger rock mass of limestone at a length scale of 30 m is approximately 1/4 of a 10-cm specimen (Kogure et al., 2006), the tensile strength S_t of the rock mass of the dolomite layer with a size effect is assumed to be 1.00–4.99 MPa, and the critical notch length l_c is estimated to be 19.8–44.3 m in this case.

5. Discussion

The stability analysis above gives a first-order estimate of the mechanical stability of the waterfall cliff, indicating that the caprock dolomite layer of the waterfall face becomes unstable and collapse when the undercutting notch length reaches tens of meters, even when the weathering condition and size effect, reducing the rock mass strength, are considered for the rock strength estimate. However, such a long notch is not observed at the bottom of Horseshoe Falls where actual undercut is no longer than 10 m (Fig. 2C). The existence of a tunnel within the waterfall face behind the water drop, from which one can see the back of the water curtain through a window, also indicates the shortness of the undercut. Also, literatures or photographs documenting the shape of the waterfall in the past do not indicate the existence of such a long notch beneath the waterfall (e.g., Dunn, 1998). Furthermore, processes which form a long undercutting notch into the lower shale layer are hardly specified: backward flow erosion of the falling water does not seem strong enough to erode the shale layer having almost the same rock strength as the upper dolomite layer (Table 1). Unlike a small gully head in non-consolidated soils (De Ploey, 1989; Bennet et al, 2000; Flores-Cervantes et al., 2006), plunge-pool water turbulence is unlikely strong enough to cause the erosion on the hard rock at the bottom of the waterfall face, where the water in the plunge pool (tens of meters deep) reduces flow velocity after the flowing water drops to the plunge-pool surface. Although it is hard to confirm the existence of possible undercut beneath the plunge pool water surface, we assume from these reasons that the undercut by plunge pool water flow is unrealistic. Instead, differential frost weathering which can occur more strongly on the well-bedded shale layer, or ice jam pressure within the Great Gorge when the Niagara River had entirely been frozen (Dunn, 1998), could be a cause of slight depression of the lower portion of the waterfall face.

In addition, the plan shape of the crest line of the cliffs at and around the waterfall is arched and hence the cliff of waterfall face is laterally supported by surrounding bedrock (Philbrick, 1970), so that this 1-D analysis of stability may underestimate the critical notch length. Therefore, it is likely that the recession of Horseshoe Falls can be occurring as a result of detachment of small rock blocks on the waterfall face, both in upper dolomite and lower shale layers, rather than by an episodic, gravitational mass collapse of the caprock dolomite of Horseshoe Falls due to the notch development.

This result is consistent with our previous study (Hayakawa and Matsukura, 2009) which examined the rate of recession of Horseshoe Falls assuming that the surface water flow is a predominant factor causing gradual erosion of waterfall face. The rate of Horseshoe Falls recession is well explained by a dimensionless index of erosive force and bedrock resistance, which postulates that surface water flow causes the detachment of the rock particularly at the crest of the waterfall on which the stream directly forces the rock to be eroded (Hayakawa and Matsukura, 2003, 2009). The dominant process of the waterfall recession is thus likely fluvial. Cavitation is a possible process occurring at the crest to cause the detachment of the upper dolomite (e.g., Philbrick, 1970), and toppling may also occur by surface flow pressure (Lamb and Dietrich, 2009). Whereas, abrasion or erosion by sediment particle impact unlikely operates on the face of the waterfall because almost no sediment is transported in the Niagara River due to the sediment trap by upstream Lake Erie and other lakes of the Great Lakes.

Frost weathering actively occurs in the site under the cold climate, and the rock surface of the cliffs along the Great Gorge is commonly weathered. The lower shale layer especially seems vulnerable to the weathering due to the dense bedding planes and joints. The overhanged shape of the profile of the cliffs at and around the waterfall can therefore be the result of the relatively intense weathering on the lower shale layer compared to the upper dolomite layer. However, the rate of cliff retreat by frost weathering is generally low: for instance, the cliff retreat rate in unconsolidated pumice deposits by freeze-thaw action is only 0.01 m y^{-1} (Matsukura, 1988, 2008). Although the weathering rate can differ with different lithology and environment, the intensity of frost weathering is unlikely to exceed that of fluvial erosion in the study site causing such the rapid (1 m y^{-1}) recession of the waterfall.

6. Conclusions

The stability analysis using the cantilever beam model suggests that Niagara Falls unlikely recedes episodically by the collapse of the waterfall face with the development of a long undercutting notch, but more likely recedes gradually by the fluvial erosion of surface water flow and gradual detachment of small particles from the fractured rock of the waterfall face. Frost weathering may be responsible for keeping its overhanging shape, but does not seem to excess a significant role in the waterfall recession. This inference should be necessary for the assessment of future changes in Niagara Falls, which critically affect the safety of the surrounding roads, trails and tunnels. Further studies such as precise measurement and monitoring of the waterfall shape are necessary to specify the actual process of recession occurring in the Niagara Falls.

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Tables and figures

Table 1. Summary of rebound values (R_N) of Schmidt hammer test obtained by the repeated impact method. Numbers are averaged for each rock type and weathering condition, with those in parentheses show the standard deviation. See also Fig. 3.

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.

Fig. 2. (A) Classical explanation of the profile of Niagara Falls given by Gilbert (1890, plate 8). Note that the name of the rock formation is as of then which does not match the present geological classification. (B) Simplified profile of Horseshoe Falls after Philbrick (1970). (C) Left side cliff of Horseshoe Falls, showing small amount of undercutting.

Fig. 3. Results of Schmidt hammer test on the bedrock of and around Niagara Falls, using the repeated impact method. The data of dolomite layer are shown with rectangle plots and those of shale/mudstone layers with white circle plots. Black solid lines indicate the data for fresh bedrock, whereas gray lines for weathered bedrock. The small numbers besides the lines indicate the site number shown in Fig. 1A.

Fig. 4. A schematic illustration of cantilever beam model describing stress distribution inside a cliff.

Table 1.

	Weathering condition	
	Fresh	Weathered
Dolomite	53.4 (4.7)	31.7 (4.0)
Shale/Mudstone	51.3 (3.4)	29.7 (1.4)
Average	52.3	30.7

(%)