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Final Report
RC-1526

Estimate of Cliff Recession Rates for the Baraga Cliffs

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A section of highway US-41 seven miles north of Baraga, MI runs along a 100 foot high cliff overlooking Keweenaw Bay. Since construction of the highway, cliff recession has advanced to a point where it is allowing the undercutting of the guardrail system of the highway and threatening the highway’s overall stability. A research program was conducted to determine the cliff’s recession rate and if the highway should be relocated. The analysis included investigating variations in shore platform widths, environmental factors, and rock characteristics. Laboratory testing of the cliff rock included point load testing and uniaxial compressive testing, while the rock quality designation (RQD) and rock mass rating (RMR) were determined from the rock core drilling. Factors affecting the rate of cliff recession are: (1) rock weathering and water migration from surface water as well as from water flowing above low permeability layers within the cliff face rock; (2) removal of weathered cliff talus material at the base of the cliff by long shore currents and wave action; and (3) the long term development of a stable talus slope at the base of the cliff. It was found that the average cliff recession rate was between 0.15 and 1.5 inches per year but that various sections of the cliff were regressing at a faster rate due to more localized factors. Survey data of the stable slopes to the south of the cliff indicate that stable slopes develop at between 30° and 33° slopes. It is likely that the Baraga Cliffs will naturally evolve to this slope angle similar to the slopes to the south of the cliffs. It is recommended that the highway be relocated to a position beyond where a stable slope will develop. This recommendation, however, is premised on a stable talus slope forming and successful vegetation developing on the slope. This also assumes that the lake levels remain at their current level or near the long term lake average.</td></tr>
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Executive Summary

Currently, cliff recession is threatening highway US-41 located on a 100 ft sandstone cliff approximately seven miles north of Baraga, MI. The recession has advanced to a point where it is allowing the undercutting of the guardrail system for the highway and threatening the stability of the highway. A research program was conducted to determine the recession rate and if the highway should be relocated. The cliff recession analysis included investigating variations in shore platform widths, environmental factors, and rock characteristics. Laboratory testing and drilling data included point load testing, uniaxial compressive testing, rock quality designation (RQD), and rock mass rating (RMR) values for the cliff rock mass. Factors affecting the rate of cliff recession are: (1) rock weathering, (2) surface water accessing the top of the cliff from highway runoff, (3) ground water flowing through the permeable sandstone and above low permeability layers within the cliff rock; (4) removal of weathered cliff materials known as talus material at the base of the cliff by long shore currents and wave action; and (5) the development of the talus slope at the base of the cliff, which acts as a barrier to further recession until it is removed by the long shore current. It was found that the average cliff recession rate was 0.15 to 1.5 inches per year but that various sections of the cliff were regressing at a faster rate due to more localized factors. The section with the most advanced recession, which is closest to the highway, appears to be recessing at a faster rate due in part to water accessing the face of the cliff. Although this does not appear to be a large amount of water, it is sufficient to accelerate the erosion

process. Since the recession of the cliff has advanced to a point where it is beginning to affect the stability of the highway, it is recommended that action be taken as soon as possible to relocate the road to a more stable position with respect to the cliff. Survey data of talus slope angles as well as stable slopes to the south of the cliff indicate that stable slopes develop at between 30° and 33° slopes. It is likely that the Baraga Cliffs will naturally evolve to this slope angle similar to the slopes to the south of the cliffs. It is recommended that the highway be relocated to a position beyond where this stable slope will develop. This recommendation, however, is premised on a stable talus slope forming and successful vegetation developing on the slope. This also assumes that the lake levels remain at their current level or near the long term lake average.

INTRODUCTION[1]

In the mid-1950's the Michigan Department of Transportation (MDOT) rerouted a portion of US Highway 41 north of Baraga MI from a more inland route to a more scenic route along a cliff overlooking Lake Superior. This section of highway section is approximately 0.5 miles in length, and is located near the community of Keweenaw Bay, seven miles north of Baraga, MI, as shown in Figure 1.

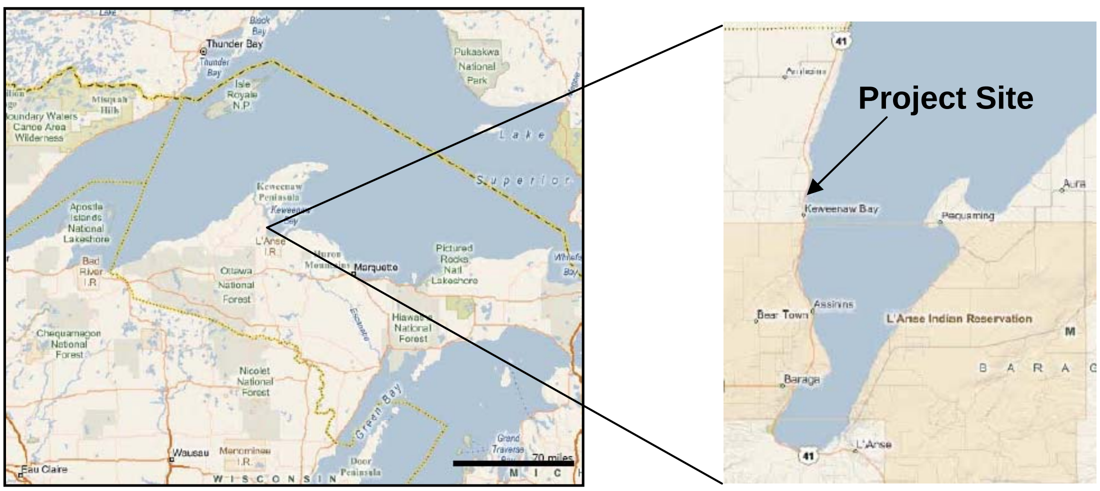

Figure 1: Location of Jacobsville Cliffs threatening US-41.

Unfortunately, due to cliff recession the cliff has eroded and has started to undermine the stability of the highway. Figure 2 shows the shoulder of the highway with the overburden material slumping towards the cliff. Figure 3 shows the cliff just below the slumping section, while Figure 4 shows a view of the cliff from the water. In the fall of 2007 the guardrail was moved several feet toward the highway, however, this spring additional slumping was observed close to the new guardrail.

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[1] This report was adapted from a master thesis written by Alexander Williams, Civil & Environmental Engineering Department, Michigan Technological University, 2008.

The MDOT Roadside Park, a scenic turnoff located just north of the cliffs being studied, also had to have its’ perimeter fence moved in 2007. Due to these problems MDOT requested a study to analyze the stability of the cliffs, the hazard they present to the highway, and the rate at which the cliff is receding.

(a)

(b)

Figure 2: Two views of overburden slumping on the top of the cliff adjacent to the highway (a) south view and (b) north view.

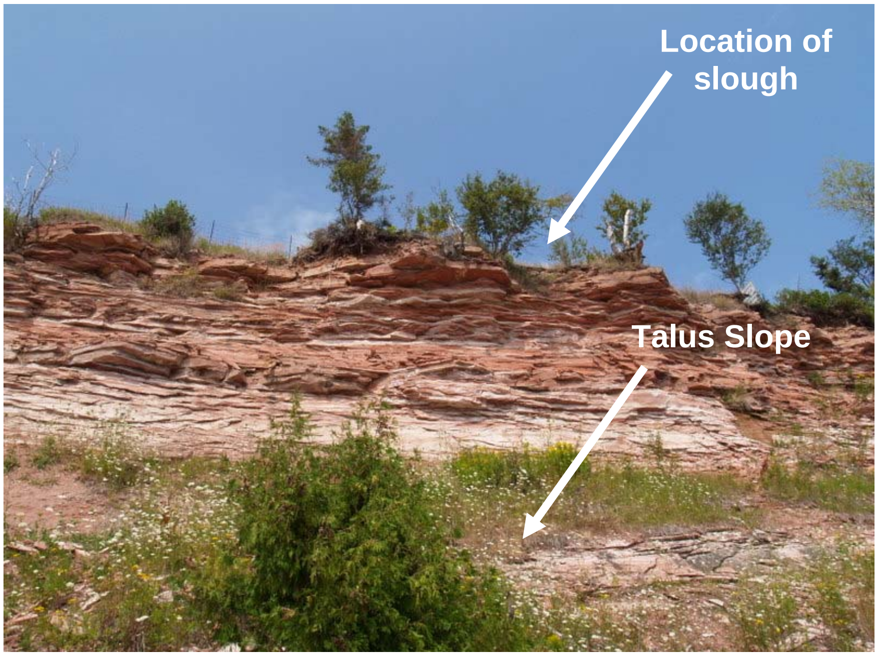

Figure 3 View of cliff just below the area show in Figure 2. Note the talus slope with vegetation forming towards the base of the cliff.

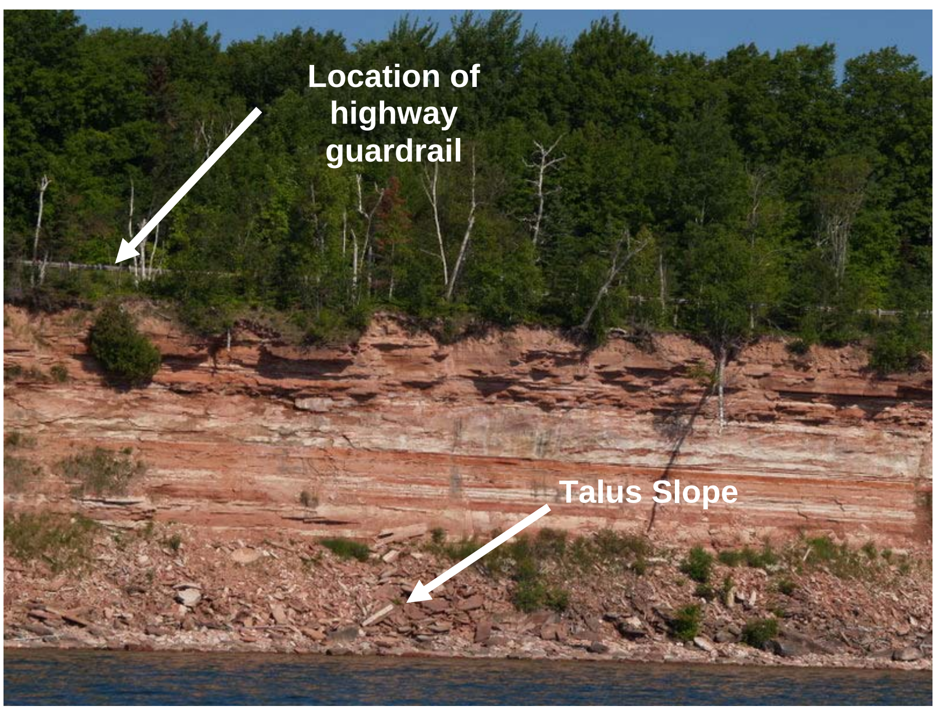

Figure 4 View of the cliff from the water. Note the highway guardrail on top of the cliff.

BACKGROUND

As with most cliff recession studies, the determination of cliff recession was difficult due to the shoreline cliff erosion process and long term lake level fluctuations. In addition, since the cliff, which is composed of Jacobsville Sandstone, is not homogeneous, erosion is not consistent from one location to another. For example, features such as seasonal streams can drastically affect the erosion of the cliff as seen in Figure 5. Figure 6 shows a section where fairly consistent erosion is occurring. For both cases however, the sandstone cliff erosion appears to be similar to coastal cliff erosion, where the majority of cliff recession research has been conducted. A main finding of coastal cliff recession is that in that it is primarily composed of both regular small losses, with occasional rapid larger losses over time (Hall 2002).

Figure 5: Seasonal stream causing accelerated erosion.

Figure 6: Section of consistent cliff structure north of MDOT Roadside Park; note the lack of talus slope formation due to direct long shore current removing the sandstone talus slope.

Coastal erosion models for ocean environments have been presented by de Lange and Moon, 2005; Budetta et al., 2000; Hall, 2002; Lee et al., 2001; Davies et al., 1998. In addition, the US Geological Survey Professional Paper 1693 titled "Formation, Evolution, and Stability of Coastal Cliffs–Status and Trends" by Hampton and Griggs, (2004) assesses the status and trends of coastal cliffs along the shorelines of the conterminous United States and the Great Lakes. In Professional Paper 1693, the erosion of coastal bluffs in the Great Lakes was reviewed and discussed by Mickelson, Edil and Guy whom concentrated on the erosion of coastal bluffs mostly in glacial till soils that are more prone to erosion than rock cliffs. These studies were reviewed for this study.

For rock cliffs an important factor for ocean cliff recession is that in all but the softest materials, cliff erosion is primarily a function of the cliff's rock strength followed by wave action and long shore current processes (Lahousse and Pierre, 2003; Stephenson and Kirk, 2000). Selby (1993) has estimated the relative contribution of various factors affecting cliff recession, which are listed in Table 1. By using a combination of the methods from previous research, a long term recession estimate for the Jacobsville Sandstone cliffs was developed.

Table 1: Erosion factors affecting cliff stability (after Shelby, 1993)

Erosion Factor	Contribution
Intact rock strength	20%
Discontinuity characteristics	
Spacing	30%
Orientation	20%
Width	7%
Continuity & infill	7%
Water Erosion	6%
Weathering	10%

Background Studies

Significant coastal cliff recession is occurring in Auckland, New Zeeland coupled with land development along the cliffs. Due to the risks posed by cliff recession to this development, research has been a high priority in determining both the short and long term coastal cliff recession rates. The cliffs around Auckland are comprised of two rock types, volcanic basalt lava flows, and a soft Flysch, from the Miocene Waitemata Group. This latter rock, though much softer than the Jacobsville Sandstone, was considered as a benchmark for the study of the Jacobsville cliffs.

The methods employed to model recession of the Auckland cliffs include the following: (1) aerial photography, which was conducted by (Brodnax, 1991) and a follow-up by (Glassey et al., 2003); (2) cadastral surveys (Glassey et al., 2003) using historical land surveys along the coast; (3) structure surveys (Brodnax, 1991); (4) geologic/geomorphic markers (Glassey et al, 2003); (5) cliff profile surveys (Glassey et al, 2003); (6) cliff face surveys (Gulyaev and Buckeridge, 2004); (7) spot shore platform width measurements (Paterson and Prebble, 2004); and (8) Full shore platform width measurements (de Lange et al., 2005).

The full shore width platform model (de Lang and Moon, 2005) was used in this research to estimate the long term recession of the Baraga cliffs. This method assumes a cliff progression occurs in three primary stages and is a function of water level variations. Figure 7 is an illustration of the three stages. The first stage assumes that a stable cliff forms along the coast at a constant water level. The cliff in maintained by vertical retreat of the cliff as the coastal erosion processes continue to cause cliff recession, i.e., the erosion process of water removing material from its base but the cliff maintains a relatively vertical profile. Stage two results when there is a water level rise and a shoreline is established at a higher elevation on the cliff face. Due to the rise in the water level a new cliff then starts to develop at the higher water level, which defined the third stage of development of the shore platform. A cliff recession rate can be estimated if the time interval between the water level rise and the width of the shore platform can be determined.

The shore platform width method assumes, however, that stages one and three remain relatively static over a long period of time.

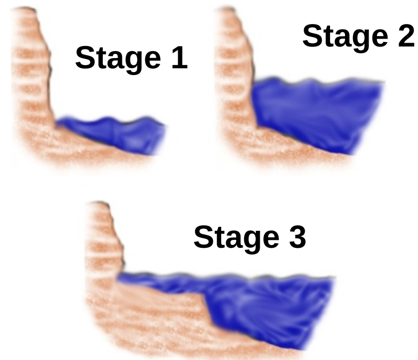

Figure 7: Illustration of shoreline platform development.

Site Information Collected

Site information collected consisted of the following: (1) aerial photography, (2) water level data for Lake Superior, (3) water depth data to create a bathymetric map of the area in front of the Baraga Cliffs, (4) cliff recession estimates from homeowners living on a similar cliff 3 km (5 mi) north of the Baraga Cliffs (5) survey data for the cliff using a LiDAR optical remote sensing instrument, (5) stratigraphy data and rock quality parameters from three boreholes, and (6) inclinometer data from one of the boreholes.

Aerial photographic surveys have been made throughout the United States since the early 20th century. In Michigan these photographs are stored at local Department of Natural Resources centers. Aerial photographs of the cliff area, however, are only available from 1962 up through 1997. The aerial photos taken in stereo-pair have approximately half meter resolution. These photos, shown in Figure 8, were used to assess both industrial impacts to the site, as well provide a rough estimate for the recession of the cliff face. The sequence of photos also shows how the lake level has changed over the past 50 years. For example, the lake levels for the year 1962, 1968, 1986, and 1997 were 601.5 ft, 601.9 ft, 602.8 ft, and 602.3 ft, respectively. Based on these lake levels, the 1986 photograph shows the high water level for the cliff for this period of time. Figure 9 shows the Lake Superior water levels for the past century and a half from 1860 to 2005. The mean lake level over this period was 601.7 ft.

A survey of the water depth was made in the summer of 2007 using a *Garmin GPS Map 720c Sounder* attached to a notebook computer. Data from the GPS unit was downloaded into *Windmill* data acquisition software, which used the coordinate and water depth data to create a bathymetric map of the area in front of the cliffs. Data was taken at two second intervals while moving at approximately 5-10 knots parallel to the shoreline at approximately equal depth intervals. A second set of GPS data was taken using a handheld Garmin GPS 76Cx unit to establish the shoreline location relative to the bathymetric data.

The face of the cliff and corresponding highway section was mapped using a LiDAR optical remote sensing instrument by MDOT personnel in the summer of 2007. The LiDar instrument uses optical remote sensing technology to measure properties of scattered light to determine the distance to the cliff. From this data a highly detailed and accurate survey map was created. A sample section of the map is shown in Figure 10. A cross-section from this data is shown in Figure 11. The cross-section is located in the vicinity of the slough that is affecting the highway.

A section of cliffs similar to the Baraga Cliffs is located about five miles north of Baraga Cliffs. These cliffs are composed of the Jacobsville Sandstone Formation and are similar in height to the Baraga Cliffs. This section of cliffs has a number of houses and other structures located on top of the cliff. Residents who live on or near the cliffs were contacted and asked to provide an estimate as to how far the cliffs adjoining their properties have receded in the time that they have lived there. These estimates were generally made based on how many times they had replaced the fencing along the cliff face on their property and the distance between old and new fence posts. Only three residents, however, had lived there for at least 25 years. Interestingly, all three provided approximately the same rate of cliff recession, which provided anecdotal data for the cliff recession.

In the fall of 2006, MDOT personnel drilled three boreholes to investigate the condition of the cliff rock and to install an inclinometer at the site. The drill holes extended to a depth of about 90 ft. Figure 12 shows the drilling crew working in October to complete the drilling, while Figure 13 shows the core from borehole #2. Figure 14 shows the approximate location of the three boreholes; BH1 was located on the south end of MDOT Roadside Park, BH2 was located along the rail line, and BH3 was located at the southern end of the guardrail. The inclinometer was installed on the south end of the cliffs in borehole BH3.

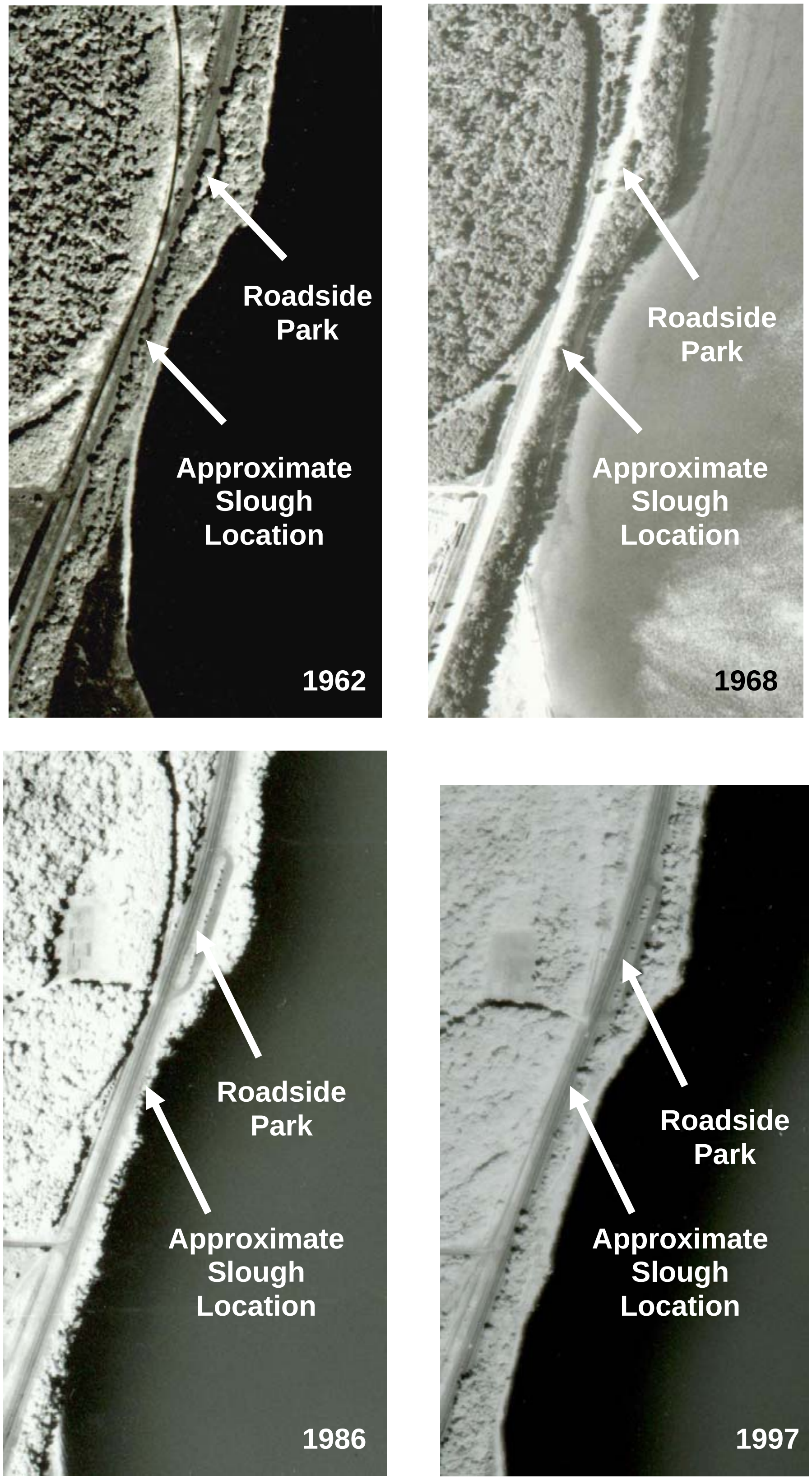

Figure 8: MDNR aerial photo showing the cliff in 1962, 1968, 1986, and 1997.

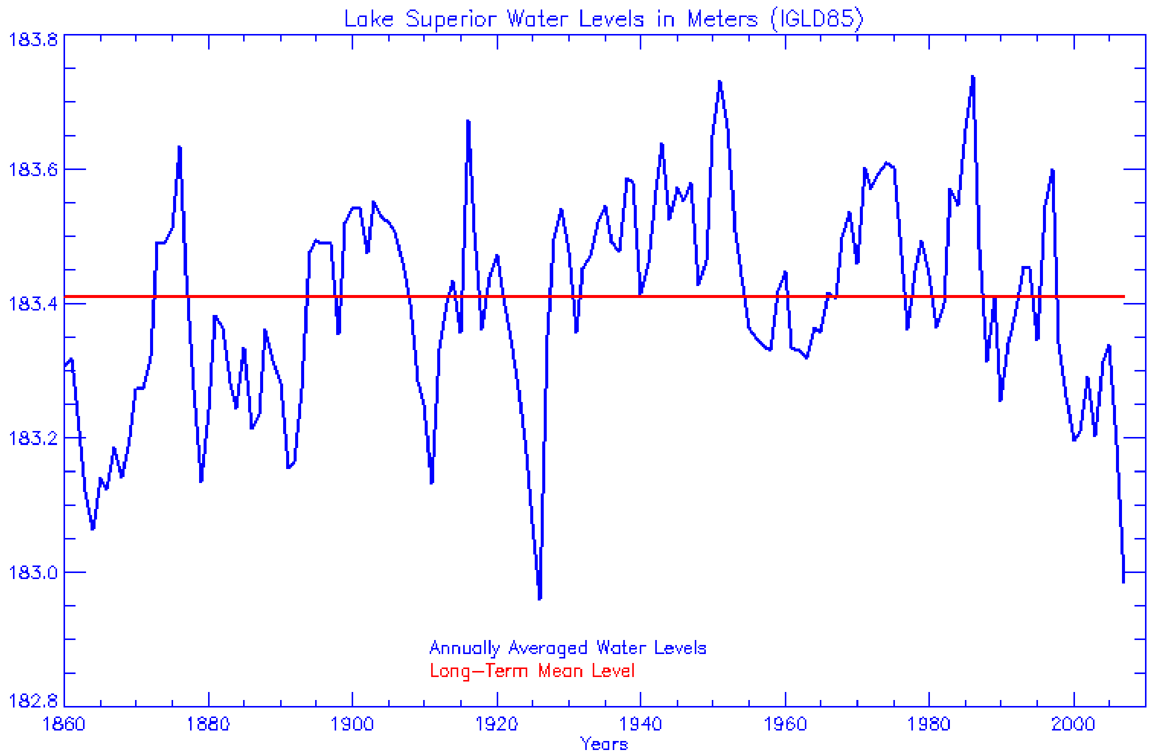

Figure 9 Lake Superior water levels from 1860 through 2005.

The cores were sent to Michigan Technological University Department of Civil & Environmental Engineering where they were tested for rock quality designation (RQD), rock mass rating (RMR), uniaxial unconfined compressive strength, and point load strength. The cores were photographed with an HD camera, and then the image was used to create a mosaic of the entire core depth.

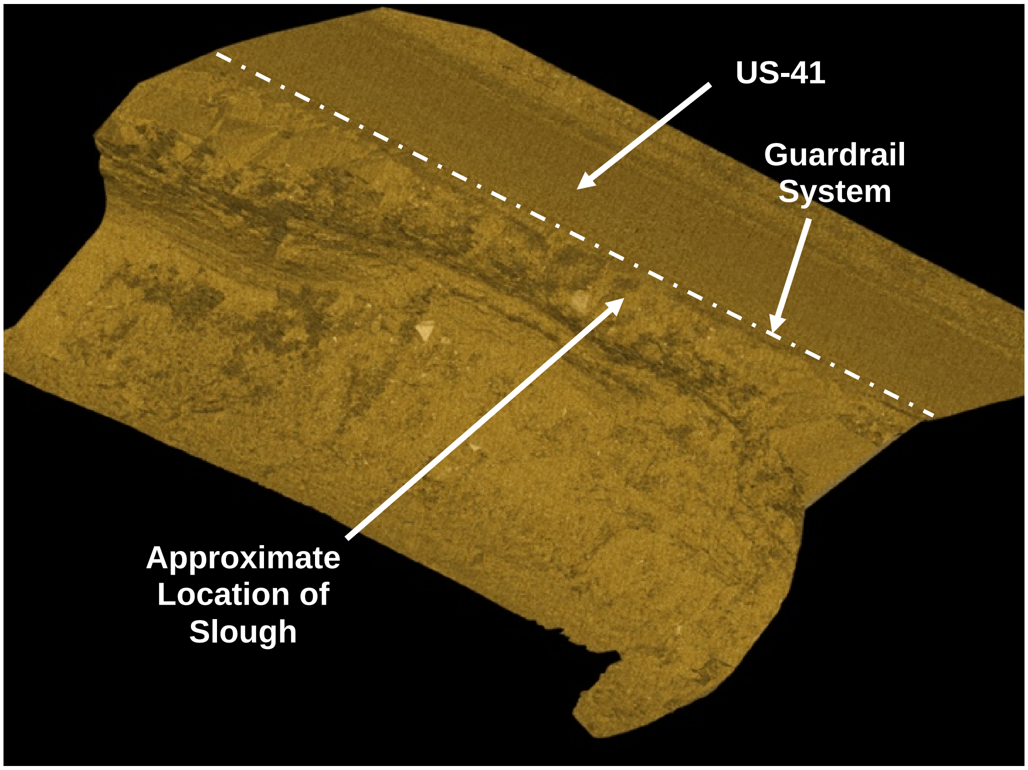

Figure 10: Section of LiDAR Model of cliff and road.

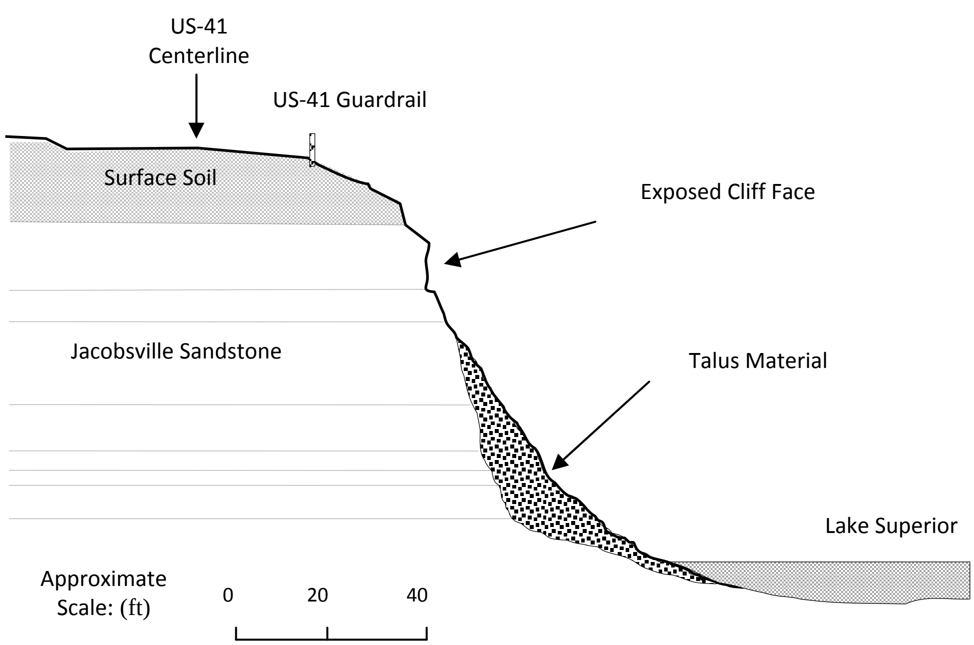

Figure 11: Cliff cross-section of at location of slough.

Figure 12: Rock cores being drilled and placed in boxes.

Figure 13: Example of HD image used to create mosaic (TH2B2).

Figure 14: Approximate location of boreholes and inclinometer.

SITE HISTORY

The main cultural feature of the Baraga Cliffs area was the Keweenaw Bay Stamp Mill located on the south end of the cliffs. The mill was constructed in 1900 and operated until 1919. There is one remaining mill structure at the site that was converted into a house and is still in use as shown in Figure 15. In addition to the Keweenaw Bay Mill, the Michigan Stamp Mill was constructed north of MDOT Roadside Park at the north end of the cliffs. The Michigan Stamp Mill was constructed between 1906 and 1909 but was never operated due to economic problems and the lack of production from a mine near Mass City, MI. The Keweenaw Bay Mill processed copper ore from a mine in Mass, Michigan about 35 miles to the west of the mill site. The only remaining building at the Michigan Stamp Mill site is located between the cliff and US-41 and shown in Figure 16. The locations of these two stamp mills are shown in Figure 17.

Figure 15: Keweenaw Bay Stamp Mill structure converted to home.

Figure 16: Michigan Stamp Mill's only remaining building.

Figure 17: Location of the Keweenaw Bay and Michigan stamp mills.

Aerial photography of the cliffs indicates that a beach, which is currently located to the south of the cliffs, was comprised of mine tailings (called stamp sands, which are discussed below). It appears that these mine tailings, which were deposited 80 to 100 years ago, were also deposited in front of the cliffs and protected the cliffs from long-shore currents. However, over time these tailings were removed by long shore currents moving to the south. Figure 18 illustrates the extent of movement of tailings southward over the forty year period of the photographs shown in Figure 8. Traces of the beach extent in 1962, 1968, and 1986, are overlaid on a photograph taken in 1997.

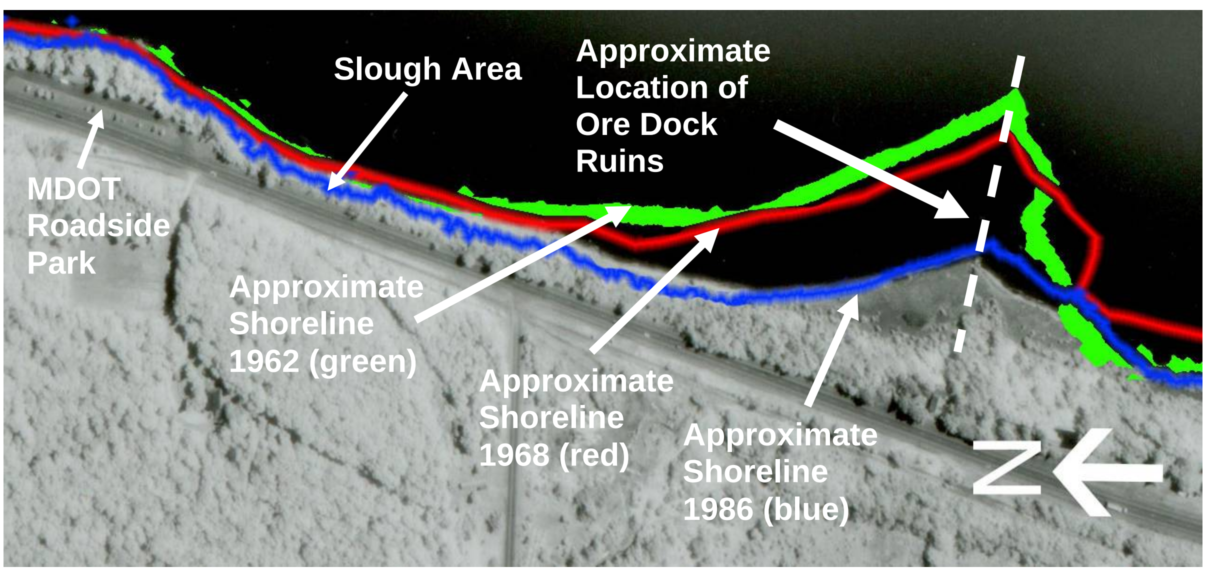

Figure 18: Erosion of stamp sands over a forty year period.

A few historic photographs and articles concerning the Keweenaw Bay Mill and the surrounding area were found at the Michigan Tech Archives. The majority of these referenced the Keweenaw Bay Stamp Mill structures. The stamp mill was used to process the copper ore by “stamping, i.e., crushing” the ore with a large concrete/steel hammer, separating the native copper from the more brittle waste rock. This process produces a large amount of “sand size” waste material called “stamp sands”. The stamp sands were mixed into slurry and moved via pipeline to where it was most economically or convenient to depose of the stamp sands which in this case was Lake Superior. After the stamping operation the copper concentrate was loaded onto ships and sent to smelting facilities. A picture of the ore dock soon after it started operations, which was used to load the copper concentrate onto boats, can be seen in Figure 19. Remnants of the docks cribbing can still be seen today.

There is no information to indicate where the pipelines were located that deposited the stamp sands into the lake. However, it appears that the stamp sands were most likely dumped off the cliff to the north of the stamp facility and dock. Over time, though, the long shore currents have moved the stamp sands south towards Baraga. Figure 20 shows a beach located just north of Baraga where stamps have been deposited by the long shore currents. However, the ore dock also acted as an obstruction and thus created a “stamp sand” peninsula surrounding the ore dock as shown in Figure 18. Currently though, the stamp sand from a large section of the dock (timber cribbing) has been moved by long shore currents and this portion of cribbing is exposed in the water. With the current low lake level, the timber crib portion of the dock is only about half a meter or so below the water line and forms a serious navigation hazard to boats.

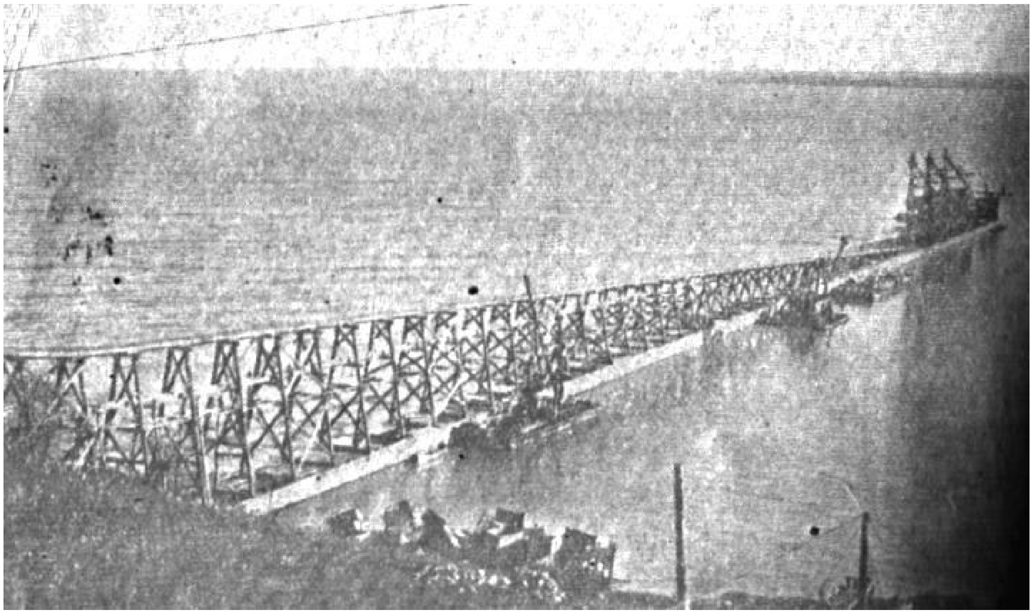

Figure 19: Ore dock at the Keweenaw Bay Mill apparently soon after opening. (Michigan Tech Archives)

The U.S. Army Corps of Engineers has been working with the Keweenaw Bay Indian Tribe in a project to remediate the stamp sands deposited from the Keweenaw Bay Stamp Mill, which have migrated southward unto their reservation. The Army Corps of Engineers investigated the stamp sands for pollutants and made recommendations for remediation. The Corps estimated the amount of stamp sands deposited at the beach shown in Figure 18 to be more than six billion pounds or about a million cubic yards (KBIC, 2006).

Since the stamping facility ceased dumping stamp sand in 1919, it is assumed that a significant amount of stamp sands had already migrated south prior to the 1962 photographs shown in Figure 21 and that a much larger amount of stamp sand was located north of the dock facilities. Since the cliffs form a somewhat protected cove in this area, it is likely that the stamp sands were originally deposited north of the dock in this cove, which would have formed an artificial beach in front of the cliffs. It is possible that one reason for US-41 to have been located as close to the cliffs as it was is that the cliffs were then more protected from the long shore currents and wave action, which would have prevent or at least reduced the rate of cliff recession.

Figure 20: Stamp sand deposited from the cliffs site on a beach just north of Baraga, MI.

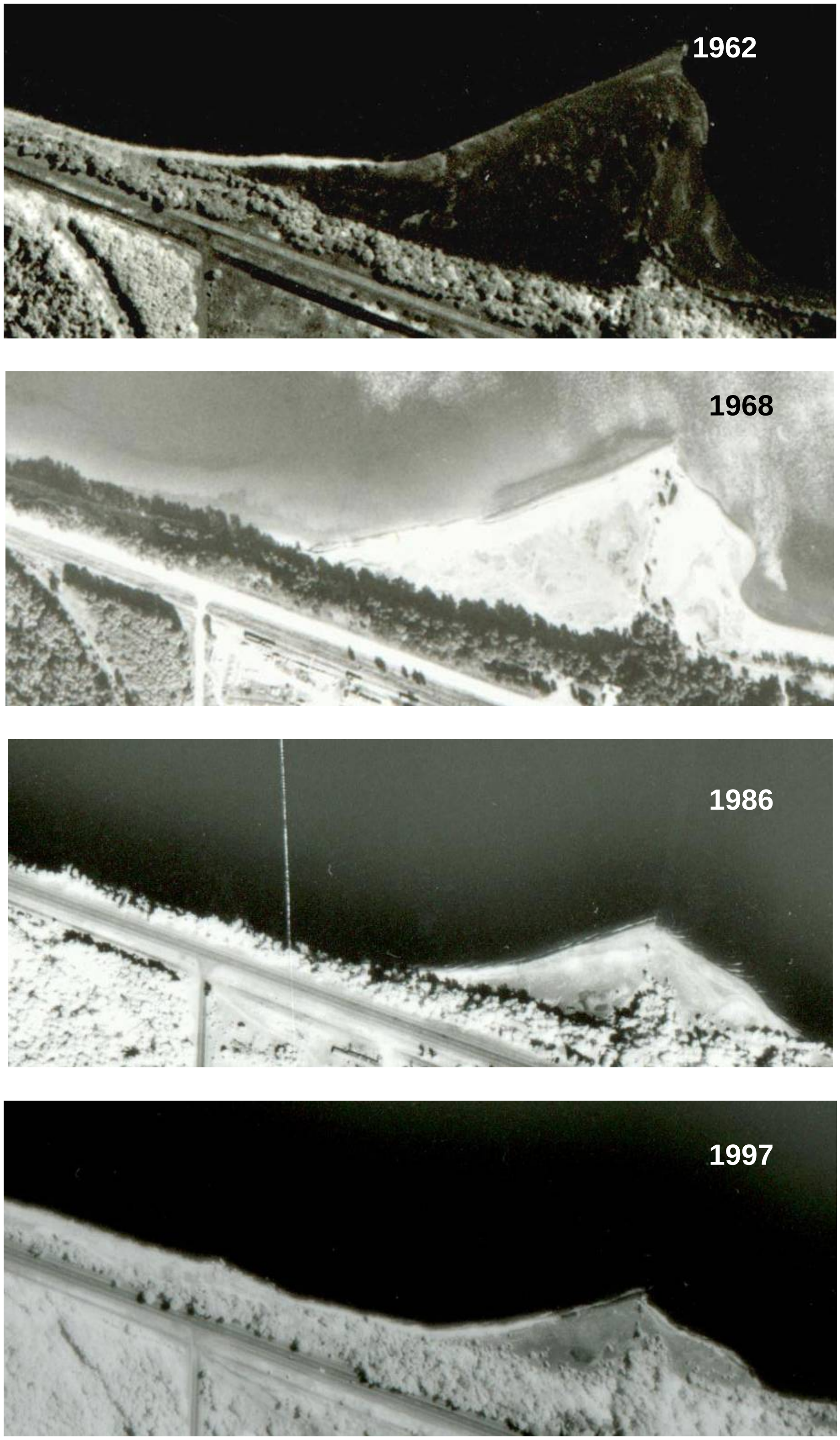

Figure 21: Protective beach recession seen in 1962, 1968, 1986, and 1997.

CIFF GEOLOGY

The cliffs are composed of Jacobsville Sandstone Formation, which is associated with the Lake Superior segment of the Mid-continental Rift System as it began to subside relative to the edges of the rift zone during the Pre-Cambrian age (Kalliokoski, 1982). The formation is approximately 3,000 feet thick and composed of fluvial sequences of feldspathic and quartzose sandstones, conglomerates, siltstones, and shales. The formation is exposed at both the western and eastern ends of the Upper Peninsula but greatest exposure is in the Keweenaw Bay area east of the Keweenaw Peninsula. Figure 22 illustrates the local geology in the Keweenaw Bay area. The Jacobsville Sandstone was overlain by the Paleozoic sediments of the Michigan Basin. Subsequent erosion removed most of this rock with the exception of a couple of small remnants located near the Baraga Cliffs. One remnant is called Limestone Mountain, and is a lower grade dolomite. Limestone Mountain is located approximately 11 miles west from the cliffs.

Jacobsville Sandstone is a very attractive reddish-brown stone with some sections having leaching with alternating oxidized (red) and reduced layers (white). The sandstone has been used as an architectural building stone throughout the Midwest United States and as far east as New York City. The rock shows its’ origins clearly on rocks such as that seen below in Figure 23.

Figure 22: Map of Keweenaw Bay area with Jacobsville Sandstone (tan color), the Portage Lake Lava Series (orange and brown color) to the North, and the Baraga Group -Michigamme Formation (purple color).

Figure 23: Sample of sandstone showing ancient lake features

ROCK MASS PROPERTIES

In the fall of 2006 three boreholes, approximately 85 ft in length were drilled from the top of the cliff. The rock core was drilled using a NX 2.125 in diameter, 5 ft long, diamond core barrel. The rock core was used as the basis for evaluation of the rock mass properties including rock quality designation (RQD), rock strength, and rock mass rating (RMR). A High Definition (HD) mosaic of the rock cores was created and used to find patterns in the bedding layers. A small version of this mosaic can be seen in Figure 24. This figure shows the entire length of core but is stretched so that layering can be seen throughout the three cores.

Rock Quality Designation (RQD)

As the rock core was retrieved from the core barrel it was measured to determine the Rock Quality Designation (RQD) value. RQD is calculated using Equation 1, where l_{10} is the length of core greater than 10 cm (≈4 in.) in length added together, and l_{total} is the total length of the core run, which was generally five feet.

$$RQD=\Sigma(l_{10}/l_{total})*100\% \qquad (1)$$

The core had relatively high RQD values between 80 and 100 percent. Almost all fractures occurred in the silt and clay lenses, which occurred irregularly within the overall stratigraphy of the formation. Upon drying, the samples were prone to fracturing due to desiccation of layers with high clay contents.

Figure 24: Rock cores in mosaic showing bedding planes and discontinuities

Rock Strength

Samples were cut from sections of rock to a 2:1 height to diameter ratio. The cores were then ground to precisely parallel edges to ±0.001 inches using a surface grinder. These cores were then tested in uniaxial compression using a 100 kip Instron compression testing machine. Displacement was measured using a clip deformation gauge attached to the rock specimen. The results as provided in Table 2 show an average uniaxial compressive strength of 4.9 kips per square inch (ksi), similar to concrete with a standard deviation of 2.1 ksi. The Young's modulus averaged 5,400 ksi with a standard deviation of 2,300 ksi.

Table 2: Uniaxial Strength and Young's Modulus for Jacobsville Sandstone

BH 1		
Depth (ft)	Stress at Failure (ksi)	Young's Modulus (ksi)
12	5.2	5800
24	3.9	4700
34	2.1	5500
40	2.0	3000
44	3.4	5000
50	6.2	5500
54	6.8	6800
57	5.3	4900
60	5.1	3700
Average	**4.2**	**5000**

BH 2		
Depth (ft)	Stress at Failure (ksi)	Young's Modulus (ksi)
10	10.7	13400
17	2.1	3700
25	4.4	3800
39	2.1	3700
46	5.7	3900
52	3.2	10500
57	7.5	5900
Average	**5.1**	**6400**

BH 3		
Depth (ft)	Stress at Failure (ksi)	Young's Modulus (ksi)
13	6.1	5600
19	4.7	4300
25	6.4	5000
32	4.8	4400
40	2.7	3700
47	8.3	6900
52	4.9	4800
57	4.5	5000
Average	**5.3**	**5000**

Samples were also tested in a point-load device to confirm the strength of the rock in sections where a uniaxial sample could not be taken. The point load device used to test these samples is shown in Figure 25. Results of the point-load test are provided in Table 3.

Figure 25: Point load test device

Table 3: Point-load test results

BH 1			
Sample #	Stress at Failure (psi)	Force at Failure (lbf)	Depth of Sample (ft)
1	600	3000	12.5
2	250	1250	24.5
3	250	1250	34.5
4	350	1750	35.5
5	200	1000	45
6	150	750	55
7	200	1000	61
Average	**300**	**1400**	

BH 2			
Sample #	Stress at Failure (psi)	Force at Failure (lbf)	Depth of Sample (ft)
1	250	1250	9
2	300	1500	14.5
3	300	1500	22.5
4	300	1500	25
5	200	1000	42
6	150	750	49
7	200	1000	51
8	300	1500	59
Average	**250**	**1250**	

BH 3			
Sample #	Stress at Failure (psi)	Force at Failure (lbf)	Depth of Sample (ft)
1	250	1250	11
2	250	1250	22.5
3	200	1000	27
4	250	1250	30
5	300	1500	33.5
6	200	1000	41.5
7	300	1500	55
8	200	1000	55.5
9	150	750	59
Average	**200**	**1200**	

The samples were tested on their circumference direction. Though the Jacobsville Sandstone is anisotropic, efforts were made to minimize the amount to which this would affect the results by only including those samples which did not fail along bedding plains. Point load measurements can be correlated to uniaxial strength using Equation 2 (Rusnak, 2000). Where UCS is the uniaxial compressive strength, K is the conversion factor and Is_{50} is the point load strength index corrected to a diameter of 50 mm (≈2 in). Values for K have been suggested as low as 12 and as high as 30 (Rusnak, 2000). The results from this research indicate that the constant "K" for the Jacobsville Sandstone is about 17. This value agrees with the values published by (Vallejo et al, 1989) for sandstones between 15 and 22.

$$UCS=K*Is_{50} \tag{2}$$

Rock Mass Rating

Rock Mass Rating (RMR) is a measure of the overall competency of the rock mass including properties of discontinuities. Equation 3 shows that there are five factors used in the calculation of the RMR parameter. A sixth term, listed as "B" in Equation 3, is an adjustment factor that relates the orientation of the rock mass, e.g., formation bedding, to the structure that is being investigated. In the case of the cliffs, the bedding is horizontal or in a "favorable" orientation. In the case of the Baraga Cliffs, which are horizontally bedded, there would be no adjustment in the RMR parameter. The RMR is calculated from the factors provided in Table 4.

$$RMR=A1+A2+A3+A4+A5+B \tag{3}$$

Table 4: Table for evaluating RMR (After Bieniawski 1989)

A. CLASSIFICATION PARAMETERS AND THEIR RATINGS

	Parameter		Range of values						
1	Strength of intact rock material	Point-load strength index	>10 MPa	4 - 10 MPa	2 - 4 MPa	1 - 2 MPa	For this low range - uniaxial compressive test is preferred		
		Uniaxial comp. strength	>250 MPa	100 - 250 MPa	50 - 100 MPa	25 - 50 MPa	5 - 25 MPa	1 - 5 MPa	< 1 MPa
	Rating		15	12	7	4	2	1	0
2	Drill core Quality *RQD*		90% - 100%	75% - 90%	50% - 75%	25% - 50%	< 25%		
	Rating		20	17	13	8	3		
3	Spacing of discontinuities		> 2 m	0.6 - 2 . m	200 - 600 mm	60 - 200 mm	< 60 mm		
	Rating		20	15	10	8	5		
4	Condition of discontinuities (See E)		Very rough surfaces Not continuous No separation Unweathered wall rock	Slightly rough surfaces Separation < 1 mm Slightly weathered walls	Slightly rough surfaces Separation < 1 mm Highly weathered walls	Slickensided surfaces or Gouge < 5 mm thick or Separation 1-5 mm Continuous	Soft gouge >5 mm thick or Separation > 5 mm Continuous		
	Rating		30	25	20	10	0		
5	Groundwater	Inflow per 10 m tunnel length (l/m)	None	< 10	10 - 25	25 - 125	> 125		
		(Joint water press)/ (Major principal σ)	0	< 0.1	0.1, - 0.2	0.2 - 0.5	> 0.5		
		General conditions	Completely dry	Damp	Wet	Dripping	Flowing		
	Rating		15	10	7	4	0		

B. RATING ADJUSTMENT FOR DISCONTINUITY ORIENTATIONS (See F)

Strike and dip orientations		Very favourable	Favourable	Fair	Unfavourable	Very Unfavourable
Ratings	Tunnels & mines	0	-2	-5	-10	-12
	Foundations	0	-2	-7	-15	-25
	Slopes	0	-5	-25	-50	

C. ROCK MASS CLASSES DETERMINED FROM TOTAL RATINGS

Rating	100 ← 81	80 ← 61	60 ← 41	40 ← 21	< 21
Class number	I	II	III	IV	V
Description	Very good rock	Good rock	Fair rock	Poor rock	Very poor rock

D. MEANING OF ROCK CLASSES

Class number	I	II	III	IV	V
Average stand-up time	20 yrs for 15 m span	1 year for 10 m span	1 week for 5 m span	10 hrs for 2.5 m span	30 min for 1 m span
Cohesion of rock mass (kPa)	> 400	300 - 400	200 - 300	100 - 200	< 100
Friction angle of rock mass (deg)	> 45	35 - 45	25 - 35	15 - 25	< 15

E. GUIDELINES FOR CLASSIFICATION OF DISCONTINUITY conditions

Discontinuity length (persistence) Rating	< 1 m 6	1 - 3 m 4	3 - 10 m 2	10 - 20 m 1	> 20 m 0
Separation (aperture) Rating	None 6	< 0.1 mm 5	0.1 - 1.0 mm 4	1 - 5 mm 1	> 5 mm 0
Roughness Rating	Very rough 6	Rough 5	Slightly rough 3	Smooth 1	Slickensided 0
Infilling (gouge) Rating	None 6	Hard filling < 5 mm 4	Hard filling > 5 mm 2	Soft filling < 5 mm 2	Soft filling > 5 mm 0
Weathering Ratings	Unweathered 6	Slightly weathered 5	Moderately weathered 3	Highly weathered 1	Decomposed 0

F. EFFECT OF DISCONTINUITY STRIKE AND DIP ORIENTATION IN TUNNELLING**

Strike perpendicular to tunnel axis		Strike parallel to tunnel axis	
Drive with dip - Dip 45 - 90°	Drive with dip - Dip 20 - 45°	Dip 45 - 90°	Dip 20 - 45°
Very favourable	Favourable	Very unfavourable	Fair
Drive against dip - Dip 45-90°	Drive against dip - Dip 20-45°	Dip 0-20 - Irrespective of strike°	
Fair	Unfavourable	Fair	

* Some conditions are mutually exclusive . For example, if infilling is present, the roughness of the surface will be overshadowed by the influence of the gouge. In such cases use A.4 directly.

** Modified after Wickham et al (1972).

The RMR for the Baraga Cliffs was estimated to have an average value of 68, ranging between 65 and 72. This is considered a Class II rock, or good rock, with orientation of the horizontal bedding planes in a favorable condition to the loading being applied. The average factors used to determine the average RMR for the cliffs are presented in Table 5.

Table 5: Average RMR for Baraga Cliffs

Parameter	Basis	Rating
A1	UCS	4
A2	RQD	17
A3	Joint Spacing	10
A4	Joint Condition	30
A5	Groundwater	7
B	Joint Orientation	0
RMR		**68**

Inclinometer

An inclinometer tube was installed by MDOT at the south end of the cliffs in borehole No. 3 (BH3). The inclinometer was monitored regularly from the fall of 2006 through the spring of 2008. An example of the inclinometer data is shown in Figure 26. Relatively little movement was detected over the majority of the tube.

What little movement was noted was in a direction away from the cliff. What movement was detected also occurred near the top of the borehole was likely due to changes in moisture content and freeze-thaw action. An example of the inclinometer data is shown in Figure 26. This figure shows the quality of the measurements near the top of the holes was less reliable than the bottom. Though little to no movement was detected, however, this installation can provide vital warning in the unlikely event of the large scale failure of the cliff.

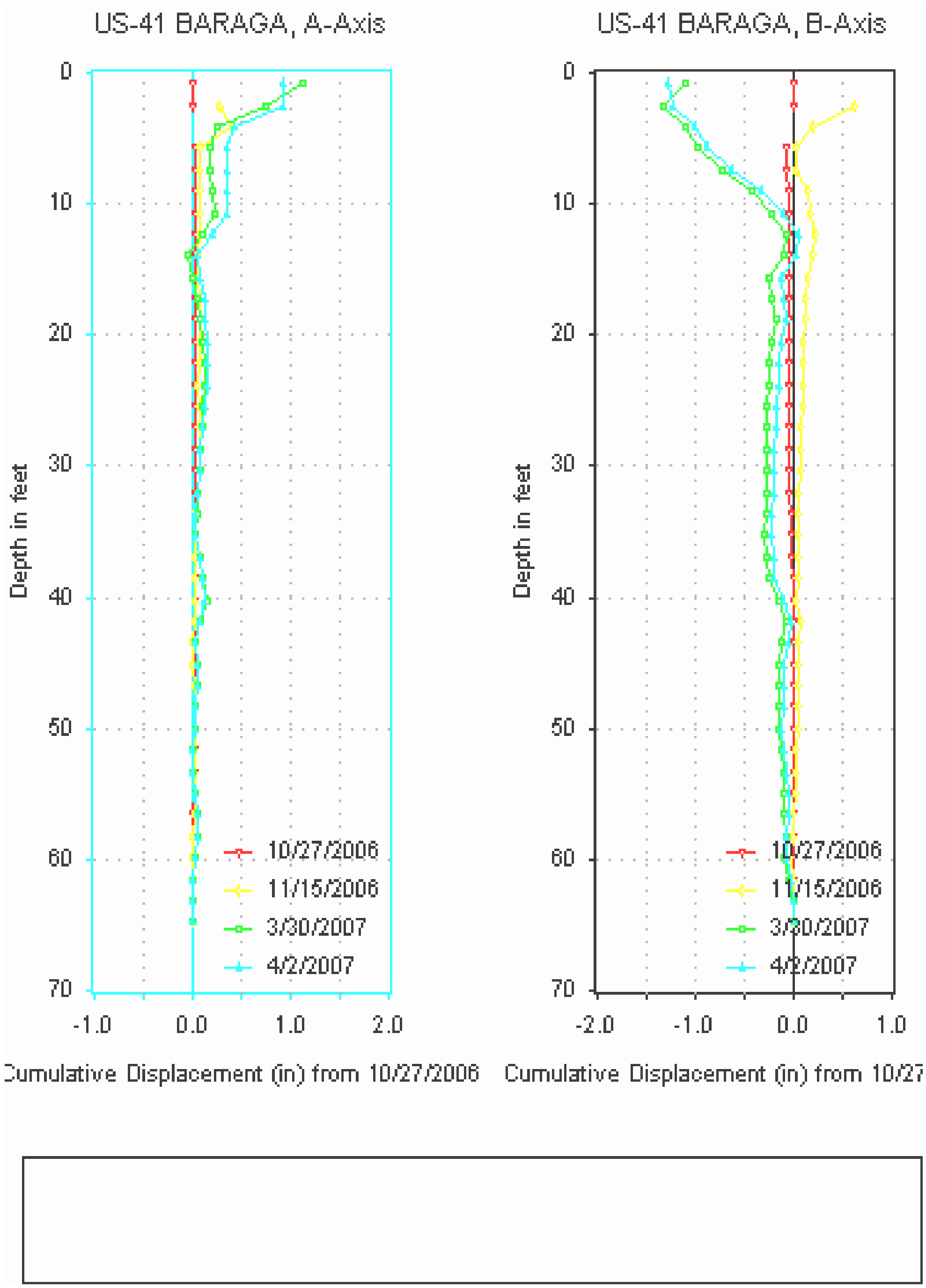

Figure 26: Inclinometer tube results

CLIFF RECESSION ANALYSIS

The recession of the cliffs can be divided into two periods, a short term period which accounts for localized failures, and a long term period which accounts for the cumulative effect of failures on the cliff as a whole.

Short Term Recession

Modeling short term recession is very difficult due to the unpredictable nature of minor failures. By examining the site a number of times over the course of two years some estimates can be made as to where and to what extent a failure will occur. Generally major failures occur in the spring and fall when variable weather causes many rapid temperature changes and snowmelt and rain create large amounts of runoff. During this time the soil layer at the top of the cliff can erode quickly and when saturated add weight to the underlying rocks. Ice jacking, (shown in Figure 27) during the winter and spring also result in significant erosion of the cliff face. Figure 27 illustrates ice jacking in the spring of 2008 on the cliff face. Interestingly, ice jacking at the Braga Cliffs appears to be associated with preexisting rock near vertical fractures as can be seen in Figure 27. The fracture crosses a number of sandstone layers and when the water freezes to ice results in a large number of fragments to become unstable and will eventually collapse. It is unclear as to the nature of the fracture system. The fractures could have resulted from the following the following possibilities: (1) tensile stresses caused by the near vertical cliff face, (2) glacial loading, or (3) tectonic crustal stresses.

Overhanging rock ledges as shown in Figure 28, which is caused by the erosion of the underling rock, is also common at the Baraga Cliffs. Sections of the cliffs with overhanging ledge rock are clearly visible from below and are due mainly to the undercutting of the less resistant rock below the ledge rock. As the rock below these ledges continue to erode, stress fractures are generated from the tension forces in the overhanging rock. Figure 29 shows a large rock fragment that recently dropped from a mid-section of the cliff. While fragments as large as 30 ft can fall from the cliff face, these events tend to be relatively localized and present in general a small amount of the cliff recession when considering the total volume of rock erosion each year.

A second indicator in regards to short term recession is the presence or lack of talus slope. A talus slope is the slope that forms at the base of the cliff from the debris falling off the cliff. Figure 30 shows the section of cliff immediate below the threatened section of the highway, while Figure 31 shows a section of cliff north of the MDOT Roadside Park. It appears from Figure 30 and Figure 31that the larger the talus slope at the base of the talus slope the smaller the rock fragments are that fall from the cliff face.

Unfortunately, an estimate of short term recession is not possible based on this work to date. It does appear that the “overall” short term recession is relatively small and the estimate provided in the next section on long term recession is a more reasonable estimate for both short and long term recession due in part to a lack of evidence for “large” scale cliff collapses.

Figure 27 Ice jacking on the cliff face.

Figure 28 Overhanging section of rock.

Figure 29: Eroded section from runoff and heavily undercut area.

Figure 30 Talus slope just below the section of cliff threatening the highway.

Figure 31 Section of cliff just north of the MDOT Roadside Park.

Long Term Recession

Cliffs adjacent to bodies of water can in general recede in the following two modes. The first mode is characterized by a vertical cliff face that recedes backwards as the talus material from the cliff face is consistently removed by long shore currents and wave action. Thus, a stable talus slope does not develop and the cliff maintains a vertical face during recession. The second mode is typified by the development of a talus slope that protects the toe of the cliff and allows the top of the cliff to continue to recess until a “stable” slope is developed. This mode is shown graphically in Figure 32. As long as the long-shore currents and wave action do not remove the base of the talus slope, the slope will remains stable.

In the case of the Baraga cliffs it is believed that a talus slope was able to form due to the artificial stamp sand beach that formed by the dumping of stamp sands over the cliff onto the cliff's shoreline. The stamp sand acted as a barrier to prevent the normal erosion of the talus slope by the long-shore currents. Once the stamping facilities ceased operations and the stamp sand started to be removed by the long-shore current, the talus slope was once again exposed to long shore currents and wave action. The removal of the talus slope thus allowed the recession of the cliff face to increase. The unusually high water levels seen in the 1980's, might have also aided in the in the increased rate of recession.

As illustrated in Figure 32, the formation of a stable talus slope assumes that the talus slope base will remain and not be removed by wave action or long-shore currents. The slope just to the south of the Baraga Cliffs appears to have recessed to a stable slope, due in part to the large amount of stamp sand that was deposited in front of the cliff as clearly shown in Figure 21. The stable talus slope on the south side of the Baraga Cliffs is estimated to be between 30° and 35° and is vegetated with young deciduous trees and underbrush. Soil cover over the rubblized rock is relatively thin but appears to be resistant to erosion. Although recession of this slope has essentially stopped, some minor erosion still is occurring due to surface runoff directed over the slope via storm runoff collection and discharge over this slope.

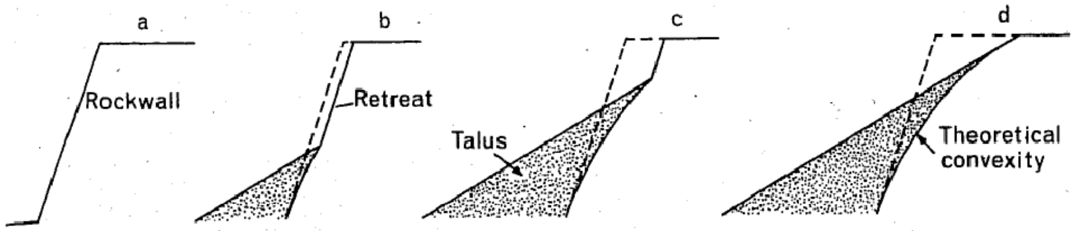

Figure 32: **A theoretical cliff in which a convex rock slope forms under the talus slope. It is assumed that there is no talus removal from the base of the slope (After Selby, 1993).**

CLIFF RECESSION ESTIMATES

Bathymetric Survey

The bathymetry of the lake bottom in front of the cliff was surveyed for the presence of a shore platform during the summer of 2007 using a combined GPS/depth finder instrument. The data from this survey was used to generate a bathymetric map of the lake bottom shown Figure 33. Although no clear shore platform was found, one section did appear to indicate the possible presence of a shore platform. This possible platform was used to estimate the cliff recession and to compare it with other recession analysis methods. The shore-platform method discussed by de Lange et al. (2005) was used.

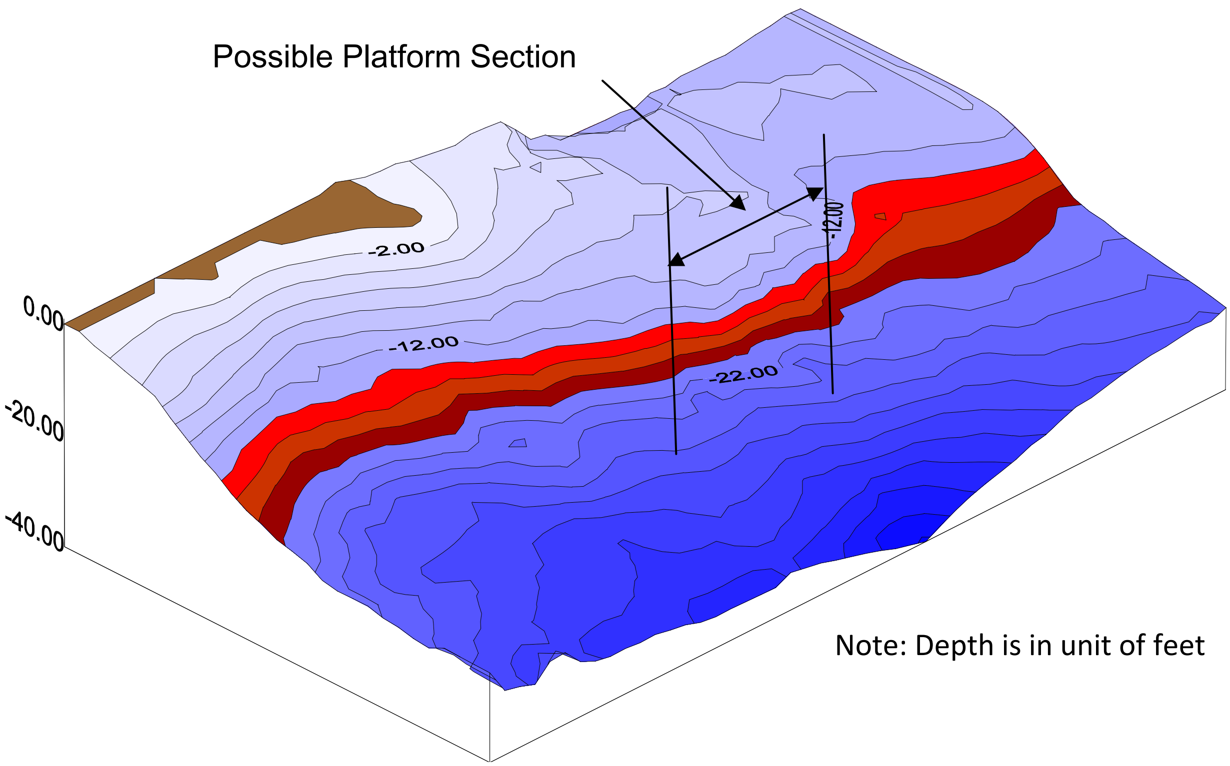

Figure 33: Bathymetric map of the shore platform and shoreline.

The method utilizes the assumption that the shore platform has not been eroded since the water level rose above the platform drop-off to its current level. Further the model assumes that the water was low enough that the cliff and platform edge were eroded as a continuous slope. The rate at which the cliff is receding can be determined by dividing the width of the shore platform by the time that has passed since the water level was below the shore platform drop-off depth. In the case of the cliffs the depth of the drop-off is 20 ft below the current levels and the distance from shore to the estimated shore platform edge was 800 ft.

The U.S. Geologic Survey (1996) fact sheet on the state of Michigan concludes that lake levels have not dropped below 20 ft since 7,000-8,000 years ago. In Figure 34 it can be seen that lake levels rose starting about 8,000 years ago. Since Lake Superior was connected to both Lake Michigan and Huron during this time, it can be assumed that the data in Figure 34 can be used to roughly estimate a similar rise in lake levels for Lake Superior. This would place the recession rate at approximately 0.15 ft/year.

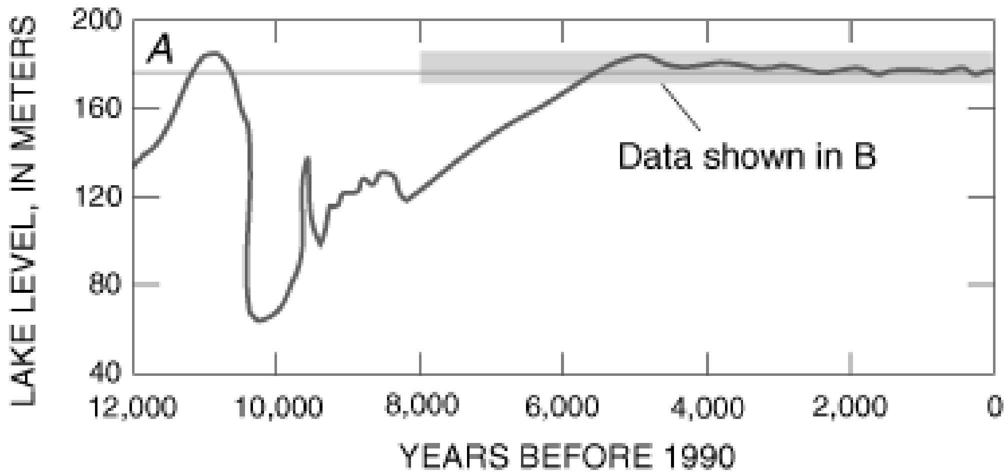

Figure 34: Historic levels of Lake Michigan and Huron (USGS, 1996)

Estimate of Resident's Cliff Recession North of the Baraga Cliffs

Three residents that live along a section of Jacobsville Sandstone cliffs, approximately five miles north of the Baraga Cliffs have provided estimates for the rate of recession for the cliffs along their property. Most residents have put fences along the cliff face and these can act as fairly accurate measures of the rate of erosion as the fence is replaced at a regular basis as it gets too close to the cliff edge. One resident had a fence they installed in 2006 and their old fence was just falling off the cliff. They stated that the old fence had been put there right when they moved onto the property in the 1960's. The old fence and new fence were 6 ft apart. Based on informal surveys similar to this of residents and measurements taken on their properties a general estimate of one foot per decade or about 1.1 in/yr was determined.

Aerial Photography Estimate

The historical aerial photographs shown in Figure 8 were used to estimate cliff recession. The aerial photographs, while not of a high resolution, did allow for a rough estimate of cliff recession for the 50 year period of approximately 1.5 in/yr. This estimate is in line with the resident estimate and the long term shore platform model.

DISCUSSION

Based on the results of the findings above, the cliff is regressing at a rate of 0.15 to 1.5 in/yr. This estimate is in line with the estimate by de Lange and Moon (2005) for cliff recession in Auckland, New Zealand of a low of 0.4 in/yr to a high of 2.9 in/yr. Although a relatively minor rate in regards to the Braga Cliffs, there is clearly more localized recession that is occurring at a faster rate. This recession has caused the surface overburden, which forms the subgrade material for the highway, to slump over the cliff threatening the local stability of the highway. Given the

RMR of about 70 and no evidence of large scale collapses, however, there is minimal risk of a large scale collapse occurring to the highway. Nonetheless, the highway is at risk of becoming unsafe in the near future as the more localized cliff recession continues. So far, the guardrail has had to be moved in toward the road. Due to this concern, a permanent solution to the stabilization of the cliff is required.

One solution is to cut the slope back to stable slope at an angle similar to the slopes to the south of the cliffs and then reroute the highway to the top of the new slope. This would stabilize the road and shoulder indefinitely as the potential for erosion would be greatly reduced. After allowing vegetation to form on the slope and placing armor stone at the toe of the slope to protect the toe from erosion very limited maintenance would be needed on the slope. Since the plan is simply speeding up a natural process the area would keep a very natural appearance. Vegetation could be planted that would allow for a view of Keweenaw Bay from the highway, i.e., low lying vegetation that would not obstruct a drivers view.

Another solution would be to move the road back to a safe position and then allow the slope to naturally recess to a stable slope. However, this plan assumes that a natural stable slope will form, similar to that shown in Figure 32, and that Lake Superior will remain at its current level or lower.

A wire frame model, which is a series of cross-section taken through the cliff (from the LiDAR data set), was used to estimate the natural angle of repose at which the slope would be stable so that an estimate of the set-back distance that the highway should be moved to. The model seen in Figure 35, shows that the talus slope at the base of the cliff rests at an angle between 33 and 38°; this angle is somewhat higher than the angle of the slope south of the cliff. Using an estimate of a 33° slope angle the highway would need to be moved away from its current location by about 66 feet.

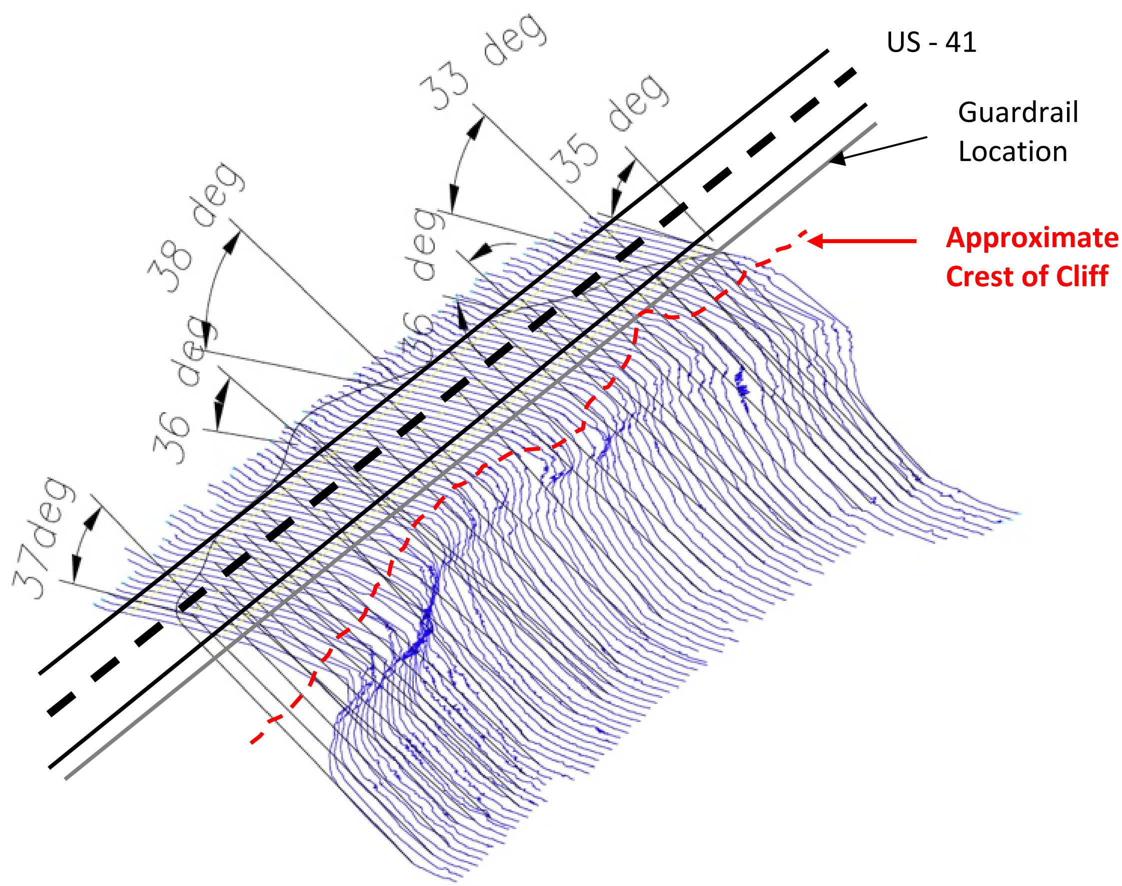

Figure 35: Wire-frame model with slope projections of talus slope

CONCLUSIONS

The main conclusions of this research are as follows:

1. Based on three approximate method it was determine that over the long-term the Baraga Cliffs are regressing towards US 41 at an average rate of between 0.15 and 1.5 in/yr. There are some sections, however, that are regressing more rapidly in the short term. Fortunately, though, there is no indication that a large scale collapse is possible.
2. The section of cliff that is now closest to the road appears to be regressing at a faster rate than the 0.15 to 1.5 in/yr average and will soon be threatening the stability of the highway.
3. As a precautionary measure the guardrail has been moved in. However, this is a temporary solution since some erosion of the surface soils has now been seen under the new guardrail.
4. It is clear that steps must be taken to ensure the stability of highway. At this point the one option that should be considered is moving the road away from the cliff a distance such that a stable slope can be created in between the road and lake.
5. Based on the natural angle of repose for the talus slope at the base of the cliff, a stable slope should form at an angle between 33° and 38°.
6. The estimate 33° to 38° degrees slopes is supported by slopes south of the Baraga Cliffs that have vegetated and stabilized at similar slope angles.

RECOMMENDATIONS FOR FURTHER STUDY

Based on this research the following are recommendations for further study on the Baraga Cliffs:

1. LiDar mapping should be conducted each year to create a database for comparison which could give an accurate estimate for the rate of recession.
2. Inclinometer measurements should be taken in the spring and fall of each year to ensure that there is no change in the current condition.
3. MDOT Roadside Park, at the north end of the cliff, affords a buffer for the highway. The cliff at the park has not been protected by stamp sands but appears to be of more competent rock. The cliff also has no talus slope below it at this point and large blocks litter the water below. This area will have to be studied further before recommendations for the remediation of the park can be made. Since the park structures and area are not immediately threatened, further investigation into how this area could best be remediated are possible and would allow for methods to be studied that may be applicable to other Sandstone cliffs such as those found in Pictured Rocks National Lakeshore.
4. An additional issue that should be studied is the variation in lake levels in the Great Lakes. Currently the International Lake Superior Board of Control controls the level of Lake Superior through the use of the Sault Ste. Marie locks. However, lake levels have risen drastically in the past and could rise

again at some point in the future. This would have serious effects on the stability of the slope and should be studied further.

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APPENDIX

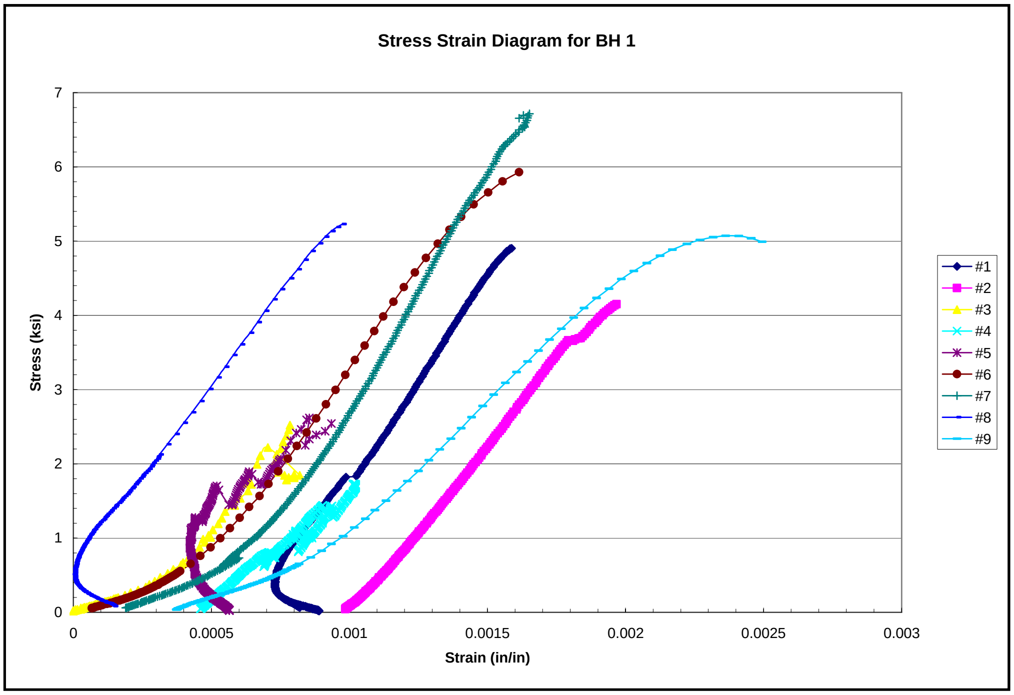

Figure 36: Stress –Strain test results for the core from borehole BH1. The test numbers are consistent with the data in Table 2.

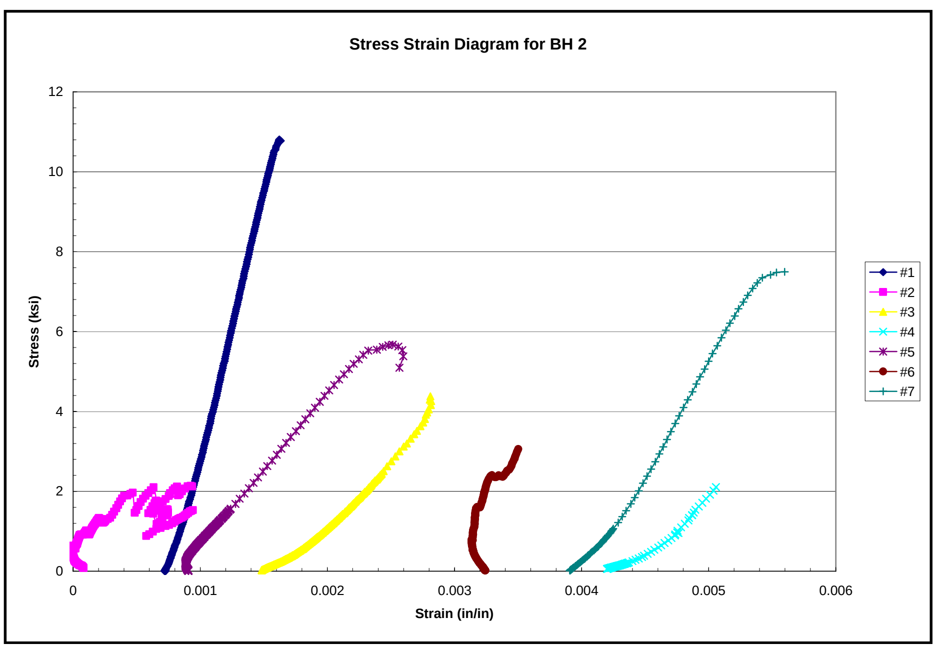

Figure 37: Stress –Strain test results for the core from borehole BH2. The test numbers are consistent with the data in Table 2.

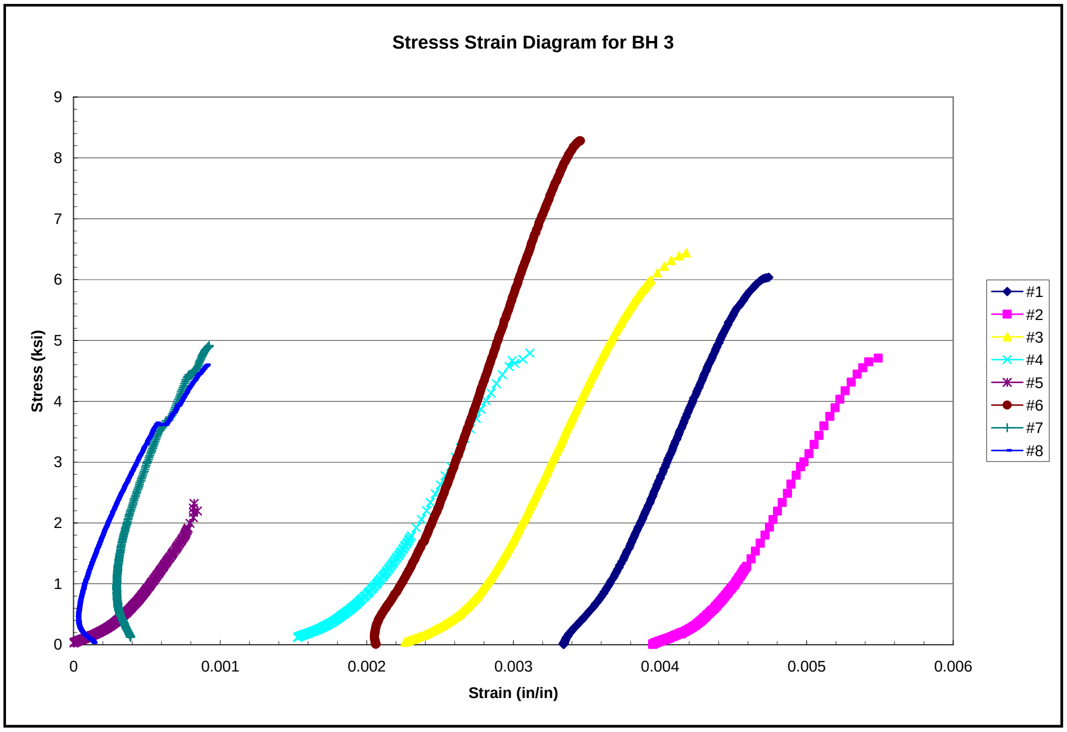

Figure 38: Stress –Strain test results for the core from borehole BH3. The test numbers are consistent with the data in Table 2.