A Case Study of Slope Stability Assessment Thames River, London, Canada

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Abstract. Three properties located on Adelaide Road, setting on top of the bank-slope of Thames River were selected as the project site for a case study. Bank slope failure caused by massive sliding and toe erosion was investigated. The mechanical regime of riverbank sliding, and toe erosion was studied. Methods of preventing slope erosion and massive sliding was discussed. Lessons learned from the case study was summarized. Following the guideline of OMNR and the regulations of long-term stable top of slope (LTSTOS) assessment of local conservation authorities is a right way to avoid an unexpected natural disaster to create a massive slope sliding.

1 Introduction

Three properties located at Adelaide Road (Highway 81), south east of Mt. Brydges, in the community of Delaware, City of London, Ontario, were selected as the project site for case study (Fig. 1). The three homes setting on top of a bluff, overlooking the Thames River, was constructed in 1969 (Brenk 2014). The bluff stands above an inward turn of a concave section of the tortuous meander's river - the Thames River. Depth from top of the bluff to the surface of river water was about 30 ft, measured on the day of June 11, 2015. Current of the Thames River is causing erosion of the bank, especially under flooding conditions during spring snow melt and rain rich seasons.

1.1 The Thames River

Thames River is one of the most southern Canadian water courses formed following the retreat of the Wisconsinan Glacier from Ontario and the upper reaches. The river is about 273 km long, as measured from the headwaters of the South Thames to Lake of St. Clair, and drains some 5,825 km^2 of land, making it the second largest watershed in southwestern Ontario (Nirupama and Simonovic 2006). Physio-graphically the Thames River basin divided into upper and lower portions at Delaware (UTRCA 1998). The land of the project site is within the boundary of Lower Thames Region Conservation Authority (LTRCA) (Brenk 2014).

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Fig. 1. The project site is located on Adelaide Road, south east of Mt. Brydges, in the community of Delaware, City of London, Ontario (From Google Map).

1.2 Geological Formation

The Lower Thames River basin has little relief, except for the incised Thames channel from Delaware to Thamesville. Much of the land surface is sand and clay plains and topography is flat to gently rolling. Two types geological plain formations dominated the lower Thames basin. The Bothwell and Caradoc sand plains are delta outwash deposits and the Ekfrid clay plain is lacustrine (MOE and MONR 1975).

The Upper Thames River basin is characterized by three lengthy moraines, numerous outwash deposits, drumlin fields and till plains. In general, the upper basin has more varied physiography with substantial reliefs. Reliefs are generally less than 50 ft and the moraines are discontinuous where they are dissected by drainages (MOE and MONR 1975).

Till plains with rolling topography constitute almost 60% of the land surface in this part of the basin. Drumlin fields are superimposed on the till plains. Moraines protrude through the till plains and form much of the western, southern, and southeastern basin boundaries.

Sand and gravel deposits in the London area were transported by melt waters and deposited as deltas where the spillways entered the glacial lake. The sand and gravel deposits are locally thick and extend to bedrock in the vicinity of the Fanshawe Dam.

Overburden covers all the lower basin and restricted bedrock outcrops occur only at Beachville and St. Mary's in the upper basin. The overburden thickness varies throughout the basin with a maximum reported thickness of approximately 300 ft in the moraine south of London (MOE and MONR 1975).

1.3 Soil Properties

Soils of the project site was developed in soil parent materials ranging in texture from heavy clays to coarse gravels. Many of the differences in texture and soil structure have been influenced by the various processes of material transport/deposit. A diagram showing grain size analysis for a sample taken from the site are shown in Fig. 2. Results indicate that the sample soil is composed of 0.3% of gravel, 41% of sand, 33% of silt and 25.7% of clay. Soil samples taken for laboratory analysis and testing were collected on June 8th/2019. Locations of soil samples taken refer to Fig. 5.

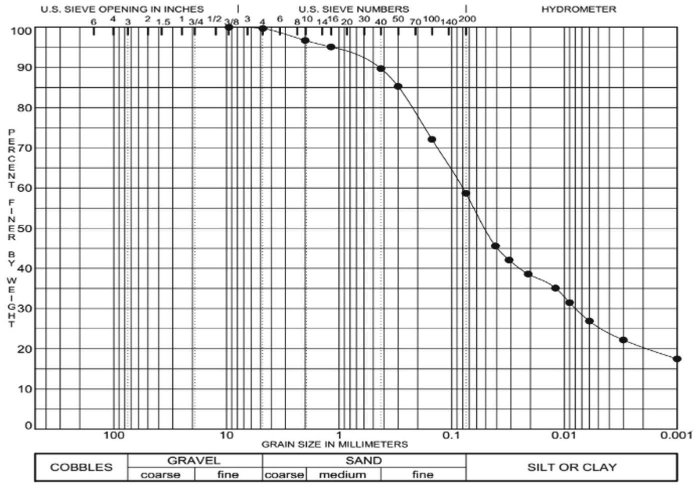


Fig. 2. Gradation curve of a soil sample taken from the site at the bottom of the riverbank within the zone of slope toe, by the author, on June 8th, 2019.

The original soil parent materials are highly calcareous and alkaline. However, the soils have developed on these materials are less calcareous as the leaching action of water on soil bases, especially calcium.

This leaching action, along with associated soil weathering, causes the development of soil horizons near the soil surface. These horizons differ from each other in properties such as texture, colour, thickness, structure, and consistence (Hagerty and Kingston 1992).

Variations of freshwater infiltration and soil drainage conditions made difference in soil formation and development from same parent materials.

Following the leaching action, the salts that originally contributed to the bonding of the particles were slowly removed by freshwater filtering through the ground. This may create the possibility to form a weak but water-rich sediment in clayey soils. The increasing in pore-water pressure, especially during periods of high rainfall or rapid snowmelt period may stimulate the favour conditions of riverbank erosion. Soil movement and porewater pressure increasing may further trigger an unexpected slope sliding.

2 Slope Conditions

The bank slope of Thames River, where three homes setting on top with rear yard facing southwest, fronting the river valley, was selected as the study site. Location of the site is in Lower Thames River water basin and close to the boundary of the Upper Thames River in the community of Delaware.

The site is in a critical condition of falling into the Thames River, as erosion of the banks is creeping ominously close to the homes (Fig. 3).

Fig. 3. Three homes on Adelaide Road are close to falling into the Thames River (Picture taking on April 17, 2013 by Mike Hensen 2013).

Home at bottom right in Fig. 3, was owned by David and Susan Shuttleworth. They bought the property and moved into house in 2001. The house was built up in 1969, right after the permit was issued. Backyard overlooking the Thames River was 40 ft long, if measured from the house to the top line of the riverbank slope (Patis 2014).

2.1 Slope Collapses

Problems of channel erosion and stream bank stabilization of Thames River was noticed in early 1971 and well documented in a report of “Flood and Erosion Control Works on The Lower Thames River From Chatham to Delaware” prepared by James F. Maclaren Limited (TRIC 1975).

Toe erosion making slope from unstable to collapse usually goes unnoticed until a significant amount of soil mass from the bank slope has been removed. A severe slope collapse was happened on March 13 to 14, 2009. A large part of land slid into Thames River and left the remain of back yard about 20 ft long in between the house and the newly formed slope top line (Brenk 2014; News Local 2009).

Falling soil piled on the toe of slope was gradually taken by river flood as solute, suspension sediment and bed load flowing transported to downstream. Toe erosion always strongly related with channel flow direction and varied with current velocity which is a function of peak flow banned with river flooding.

Another three years after the notice of the slope erosion to the land where their home standing on, a massive sliding into Thames River happened again and the owner reluctantly moved out in 2012. The further erosion was continuing and the Shuttleworth's home, showing at right bottom side in Fig. 2, was demolished on February 17, 2015 (Brenk 2015).

2.2 Peak Flow and Flooding

Floods may occur at any time of the year. Spring floods, caused by a combination of ice, snowmelt, and rain, are most frequently. Summer floods caused by major thunderstorms were experienced in the past. Probability analysis indicated a severe flood induced by tropical hurricane is also a possible occurring in autumn.

Generally, the highest monthly stream flows occur in March, with a few stream's discharging peaks in April. Usually, much higher flows occur during the March and April freshets than in other months. Freshets are the sudden raises in water level of the river, or a flooding caused by heavy rains and/or the rapid melting of snow and ice. Typically, summer floods have sharper peaks than the more frequent spring runoff floods.

Floods are closely linking with local climate and weather conditions. The prevailing winds in the region are westerly. Normal annual precipitation in the basin generally increases from the lower reaches to the headwaters, ranging from 32 in. at Chatham to 39 in. at Stratford. There is notably little seasonal variation in precipitation, with the difference between maximum and minimum, normal monthly precipitation being generally less than one inch (MOE and MONR 1975).

The snow belt area of southern Ontario is centred north of the Thames watershed, however its effect extends into the basin, causing an annual average snowfall of approximately 40 in. in the western end of the basin and approximately 68 in. in the eastern end (MOE and MONR 1975).

Peak flow is closely related to precipitations during a year and can be explained by a series of historical observations. We adopt the historical hydrological process in 1997, recorded in two hydrologic observation stations at London area, as an example. Plotting the observed total precipitation (rainfall and snowfall) versus river discharge measurements to illustrate the actual trend of peak flows during the year of 1997 (Fig. 4).

Hydrologic observation station, Thorndale is located upstream of London and hydrologic observation station, Byron is located south of London at the outlet of Upper Thames River Watershed (UTRW).

The differences in peak flows between Thorndale and Byron, when plotted on Fig. 4, show a similar pattern over the year. Discharge response to total precipitation occurred during the entire year of 1997.

2.3 Groundwater and Seepage Flow

Once precipitation infiltrates to the water table, it becomes ground water. Below the water table all materials are saturated. Soil type, composition and grain size of the subsurface material determines the availability of a seepage flow to Thames River as a base flow. At the project site, groundwater mainly recharged by the inflow from nearby higher area and by precipitation.

Surficial sand and/or gravel deposits flank the Thames River over most of its course. Extensive sand and gravel deposits along the Thames River at the Delaware section,

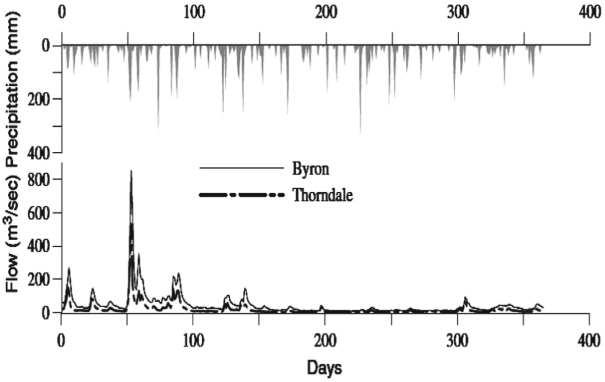


Fig. 4. Observed 1997 hydrographs at Byron and Thorndale and total precipitation at London, Ontario -- from Nirupama and Simonovic (2006).

Fig. 5. Groundwater seeping out from sandy soil was observed at project site (picture taken by Ron Xia on June 11, 2015).

especially at the area of our study, contributes groundwater discharging to the river. Phreatic surface was high and groundwater draining/seeping out at upper zone of the bank slope was observed during our site visit on June 11, 2015 (Fig. 5).

Groundwater levels reach a maximum in early spring, usually April, followed by a gradual decline to a minimum in late fall, usually October. It is uncommon for summer precipitation to result in a water level rise, although rates of decline may be slowed. This annual trend appears to have same pattern of peak flow in Thames River.

Annual groundwater fluctuation, in Thames River watershed, depends on precipitation, surficial soil type/composition, and the thickness of aquifer deposit in overburden. Shallow aquifers have annual fluctuations in the range of 3 to 10 ft. Annual water level fluctuation in deeper overburden aquifers are between 1 and 2 ft while water levels in deeper bedrock aquifers vary only a few inches (MOE and MONR 1975).

The exchange between groundwater and river water is relatively complex. Generally, river water is mainly recharged by groundwater at the study area. Water table/phreatic line, at the slope section, can be estimated by using Darcey's Law under fully saturated conditions (Fig. 6).

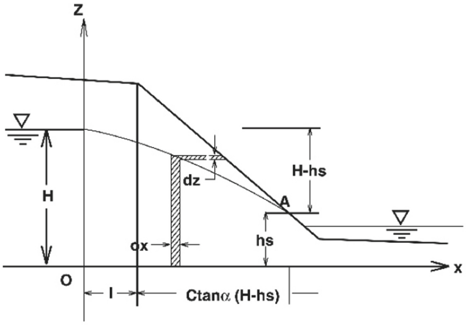


Fig. 6. Profile of a natural slope showing phreatic line computation and seepage zone (Xia et al. 2002).

Discharge per unit width along the slope face can be calculated as

$$q = -kz\left(dz/dx\right) \tag{1}$$

Where k is the hydraulic conductivity of the fully saturated zone, and $dz\ /\ dx$ is the hydraulic gradient (Fig. 5). Solving Eq. (1) by integrating with boundary conditions of $x = 0$, $z = H$, we have:

$$q = k(H^2 - z^2)/2x \tag{2}$$

where H is the distance from baseline to water table determined during geotechnical investigation or measured from ground water observation system.

Equation (2) may settle the position of water table or phreatic line through a natural slope profile and can then be used to quantify the full saturated zone of seepage.

Direction of groundwater flow is generally from higher to lower elevations and toward the channel of Thames River in our study site. However, the direction of groundwater flow is influenced by subsurface structures and underground barriers. Influence of house basement and swimming pools on groundwater flow patterns was confirmed.

2.4 Subsurface Barrier

In common, the three properties, selected for our study of bank erosion and slope stability, all have one level of basement, septic system and private water wells. Wells were used for drinking water in the old days and for watering grass after tape water facility was installed. Two of the three properties have swimming pools in their back yard (Fig. 3).

Substructures of basement, swimming pool and septic tanks are barriers for groundwater seepage flow when water level is higher than the bottoms of the substructures.

Fig. 7. Piping and mudflow was observed on bank-slope surface of Thames River at the study site (picture taken by Ron Xia on June 11, 2015).

These subsurface barriers will alter seepage flow direction, rise groundwater level, change flow path and flow velocities.

Groundwater flow will slow down at the front of the substructures, raising water levels at local areas and seeking for new paths where soil is less competent to generate concentrated flow. The raised groundwater level and increased velocity at the area where saturated fine sand, silty sand, sandy silt and/or clayey silt is encountered, dilation/quick condition may happen at the surface of the bank slope, due to the increased hydrostatic pressure and hydraulic gradient (Fig. 7).

The impact of substructure on groundwater regime was found during our investigation. Caves formed by piping water at local area was noticed. Wetland plants reed-grasses growing on the bank slop top line were observed (Fig. 8). Wetland plants or vegetation cover the top of the riverbank slope would be an evidence of groundwater rising induced by subsurface burrier at the side of a former residence.

Increase in water content, softening clay bond or other cementing agents, decrease shearing resistance. Sheet erosion and rill erosion was detected at the areas of groundwater piping out (Figs. 5 and 7). Soil erosion stimulated the processing of riverbank sliding.

2.5 Freezing and Thawing

The climate of the Thames River basin is temperate, and the proximity of lakes Erie and Huron exert a moderating influence on temperature extremes in the basin. In general, temperatures decrease from the lower reaches at Lake St. Clair to the headwater area. The lowest mean monthly temperature occurs in January, ranging from about −3.9 °C at Chatham to −6.7 °C at Stratford, while the highest mean monthly temperature decreases from 22.2 °C at Chatham to 20 °C at Stratford (MOE and MONR 1975).

Fig. 8. Reed-grass grows on bank-slope top line of Thames River at the study site (picture taken by Tudor and Ron Xia on June 11, 2015).

Approximated estimation of air-freezing index at the area, project site is located, would be in the range from 450 to 500 degree-days Celsius. Air-freezing index is a summation of the daily mean degree-day for the freezing period. A long-term mean (30 year) air freezing index can be estimated from monthly mean air temperature data published by Environment Canada (CGS 2006).

Local long-term statistic weather conditions of the site observed at the nearby weather station in Delaware community are shown in Figs. 9 and 10. The 30 years' monthly-average weather conditions were recorded from 1982 to 2012, at the Strathroy-mullifarry weather station, Ontario, Canada (Statistics D. O. 2015).

Monthly average high temperature is 27.5 °C in July and monthly average low is − 8.1 °C in January. Three months from December to February monthly mean temperature is sub-zero. Ground freezing start in December and thawing start at early March. Three higher total monthly precipitations 111, 90 and 88 mm happened in June, December, and January – see Figs. 9 and 10.

During long period of wintertime ground is freezing. Segregation ice may form in frost susceptible soils, like organic mixed with sandy/clayey silt. Along with freezing front development frost heaving generated increasingly. Following ground is frozen, thermal creaks may happen on top layer of the riverbank slope, if a frozen soil shrinking stress exceeds the maximum tensile strength of the frozen ground (Xia 1985).

In raining seasons, water may easily infiltrate into the creaks formed in winter and generate a concentrated rill flow. The rapid water flow may cause internal/external soil erosion with steep hydraulic gradient to loosen soil material, to create an open cut channel and to make erosion area dramatically enlarge.

Freezing and thawing processes may supply stimulate conditions to initial soil erosion and develop a massive movement causing collapse of a natural slope.

In springtime, after snow disappeared, frozen ground thawing starts. Meltwater initially entering down below frozen soil (Woo and Marsh 1990) will refreeze to form

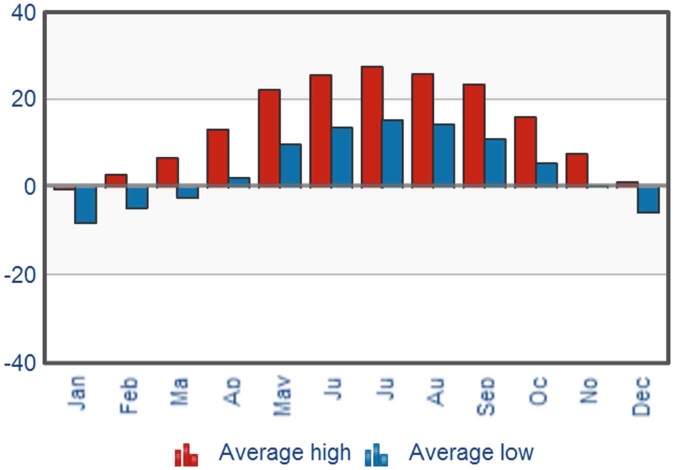


Fig. 9. Statistic overview of monthly average temperature at Delaware, Ontario, Canada (Statistics D. O. 2015)

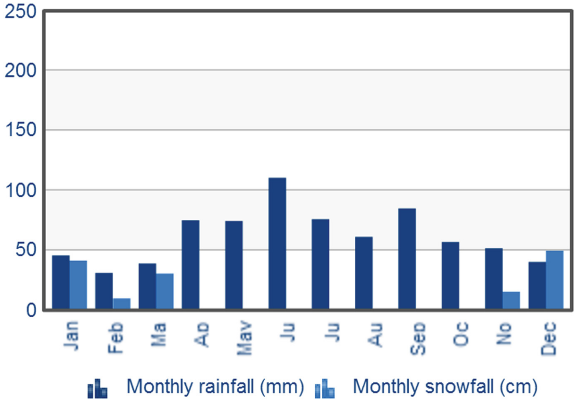


Fig. 10. Statistic overview of monthly average precipitation at Delaware, Ontario, Canada (Statistics D. O. 2015)

ground ice until the materials become impervious to further infiltration. During the re-freezing process, ice parcels and thick ground ice layer formed.

Thawing of the ground ice will release enormous voids, which will loosen soil structure, reduce shear strength and cohesion force, and the water released may act as a lubrication to reduce friction force or change friction angle at thawing front. This may strongly stimulate shallow slope failure as linear sliding and/or circular rotations.

Soil freezing depth X perpendicular to the surface of the bank slope, can be estimated with an extension to Stefan's approach and consider the release of latent heat associated with the formation of potential ice segregations:

$$X = \sqrt{\frac{2(k - SpL)Is}{Ls}} \tag{3}$$

where *Sp* is the value of the segregation potential, ***L*** is the volumetric latent heat of water to ice, *Ls* is the latent heat of soil, *k* is the thermal conductivity of the frozen soil, *Is* ground surface freezing Index and can be estimated from air-freezing index (CGS 2006). Thermal conductivity could be calculated by using the volumetric fractions of the various components of the soil (Farouki 1981):

$$k = \prod_{j}^{n} k_j^{f_J} \tag{4}$$

where *f* is the volumetric fractional content of soil component *j* which includes mineral materials (***m***), organic matter (***o***), water content (*w*), ice content (*I*) and air in voids (*a*). Their respective thermal conductivity (in W m^{-1} $^{o}C^{-1}$) are $k_m = 2.93$, $k_o = 0.25$, $k_w = 0.57$, $k_i = 2.20$ and $k_a = 0.025$. For a certain location of a slope the above components may vary with time and depth, depending on the hydrological and thermal conditions of the soils (Xia et al. 2001, Woo and Xia 1995a, b).

Coarse material with abundant interstitial voids provide ample storage capacity for the infiltrated rainwater and melt water, and their high hydraulic conductivity permits easy water movement into, out of, and within the coarse materials (Xia et al. 2002; Woo and Xia 1995a, b). Sources of seepage water may be from rainfall, snow melt or ground ice melt (Xia 1993) as well ground water from upper tableland.

Fine material may gradually leach out along with the fast flow speed of seepage and deposited at the lower portion of the slope foot or washed away by flowing water in the Thames River (Fig. 4). Velocity of groundwater seeping out can be described as:

$$V = K\frac{\Delta h}{\Delta L} \tag{5}$$

where $\boldsymbol{\Delta} h$ is difference of hydraulic energy potential, ΔL is length of flow path. Initial at the thawing season, $\Delta L = X$, which is the maximum frozen depth/thickness of the bank slope, if water seeping out the slope. Along with thawing depth growing the magnitude of $\Delta L = X$ is turning to smaller and smaller.

Velocity of seepage growing faster and faster. As ΔL changes from X to 0, the velocity V will turn to infinite. In reality, this velocity cannot be infinite but will take on extremely large values and cause fine material escaping.

Fine material escaping and pore water status changing may create a commendatory condition to form localized collapse and stimulate slope erosion. Seepage erosion is also named as subsurface erosion and was well documented (Xia et al. 2002) and widely observed at the surface of bank slope at our project site (Fig. 7).

2.6 River Water Under Cutting

As rivers and streams flow along seeking the path of least resistance, they develop different channel patterns in response to the physiography of the area. The Thames River takes on several channel patterns, but overall is best described as having a *sinuous channel pattern* or *irregular meanders (TRBSRT* 1998*).* There are, however, stretches where the meandering is more regular such as near the site of our study (see Fig. 11) and reaches where the river is fairly straight, especially downstream of Chatham (TRBSRT 1998).

A variety of erosion and depositional forms can be found as bank/slope erosion, slumping, gullies, pools, and riffles at the study site. Bank erosion is visible at the outside meander where the three houses are located on top of the steep bluff (see Fig. 2).

The vertical movement of earth material downhill is termed mass wasting. It can either occur by slide (fast) as evidenced by steep-sided un-vegetated banks, or by creep (slow). Trees grow with curved trunks, adjusting their angle to the sun as they slip further down-slope.

Rotational slips were observed in the area where material from the top of the bank slides down leaving a concave shaped bank and undercut bluffs. Erosion rates are not steady and there may not be any change in a bank for many years until a single large discharge passes through and scours the bank with enormous energy (TRBSRT 1998).

Streams of the Thames River cut through the sandy soil down to the base level of the river, creating steep-sided narrow *gulches* along its lower course. *Pool and riffle* formations are twisted. This alternating of deep (pool) and shallow (riffle) areas tends to be continuing a relatively long-term process (Fig. 11).

Fig. 11. Aerial view of tortuous meanders at the section of project site of the Thames River (picture taken by Ron Xia on June 11, 2015).

3 Developable Limits

With the intensification and expansion of urbanization along valley lands and stream corridors, the risk of exposure to natural hazards has increased tremendously in the past few decades (Botzan 2011). Under the Conservation Authorities Act, a permit is required for waterway alteration, grade change or construction in natural hazard areas. Houses standing on top of river bank slopes to obtain a permit, geotechnical assessment to define the developable limits is required (Botzan 2011).

Of particular essence in determining the developable limits is the long-term stable top of slope (LTSTOS) line (Botzan 2011). LTSTOS is an imaginary projection, over a

100-year span, of the existing top of slope (ETOS). A guideline issued by the Ontario Ministry of Natural Resources (OMNR) is utilized to define the LTSTOS.

Three types of allowance of erosion hazard limit, described in the Guideline of Ontario Ministry of Natural Resources (OMNR), are of reliable for engineering planning, designing and interest to conservation authorities' review. They are simply summarized as 1) toe erosion allowance, 2) stable slope allowance, and 3) erosion access allowance (OMNR 2002). These three elements are schematically illustrated on Fig. 12.

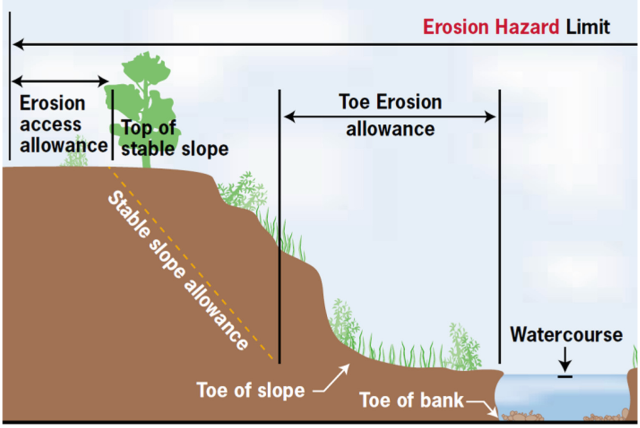


Fig. 12. Confined System, Erosion hazard limit where toe of valley slope is located less than 15 m from the watercourse (OMNR 2002).

3.1 Stable Slope Allowance

Geotechnical assessment of the LTSTOS is required in the light of the aforementioned OMNR Guideline (TRCA 2007). Slope stability verification for the section at study site was carried out using a professional commercial software "Slid-2018" developed by Rocscience Inc. for circular slip surfaces. A slope with a Factor of Safety (F.S.) equal to/greater than 1.5 is considered to be stable, as per the requirement of OMNR Guideline (Botzan 2011, OMNR 2002, TRCA 1994).

Soil conditions encountered at the study site can be summarized as the following:

- Topsoil about 200 mm in depth, overlaying a brown sandy silt to silty fine sand deposit extending to depth about 2 m, was observed.
- Light brown Sand and Gravel, underneath the brown sandy silt/silty fine sand, was in moist condition and extended to depth about 4 m.
- Grey Sandy silt till with some clay and trace of gravel was below the sand and gravel deposit and extended to depth about 8 m.
- Silt to Silt Till with some sand/clay and trace of gravel was observe below the sandy silt till and extended to bottom of the slope.
- Phreatic surface was assumed to be on the same level of river-water surface for slope stability analysis.

Results of computer analysis indicated that Factor of Safety FS = 0.87, for the existing riverbank slope at the section in our case study area. Factor of safety equal to 0.87 is less than the criterion required by Ontario Ministry of Natural Resource (OMNR). As a result, the existing slope cannot be considered as a long-term geotechnical stable slope (Fig. 13).

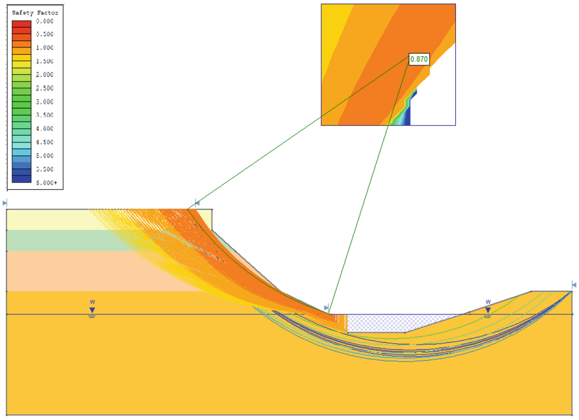


Fig. 13. Stability analysis for a section of existing slope, using Rocscience Software Slide 6.0, indicated Factor of Safety FS = 0.87 (Analyzed by Ron Xia 2019).

Back calculations were carried out on purpose of searching for long-term stable safe slope (LTSSS). With Factor of Safety equal/greater than the required criteria of FS = 1.5 for long-term stable slope, the theoretical calculated inclination would be about 2H: 1V (Fig. 14).

However, we understand that the sandy silt and sandy silt to sil strata is more erodible and a stable gradiant of 2.5H: 1V is moreh likely. Top table land of slope outside of the 2.5H: 1V inclination line would be considered as a currently long-term stable top of slope (LTSTOS).

3.2 Toe Erosion Allowance

Where the bank slope is over-steepened or subject to active toe erosion, development should be set back farther from the top of the stable slope line to ensure the development is safe from erosion and slope failure in the long term.

To determine the appropriate erosion setback for river and stream systems, engineers have to consider: 1) if the toe of the slope adjacent to the river erodes and weakens the bank, increasing the risk of slumping by active erosion, 2) the distance between the watercourse and the base of the valley wall or bank slope is 15 m or less, 3) the encountered soil types and hydraulic conditions including bank full flow velocity and the competent flow velocity of the river/stream.

A table of minimum toe erosion allowance - where river is within 15 m of slope toe (OMNR 2001) is always be applied in the erosion hazard assessment (Table 1). To

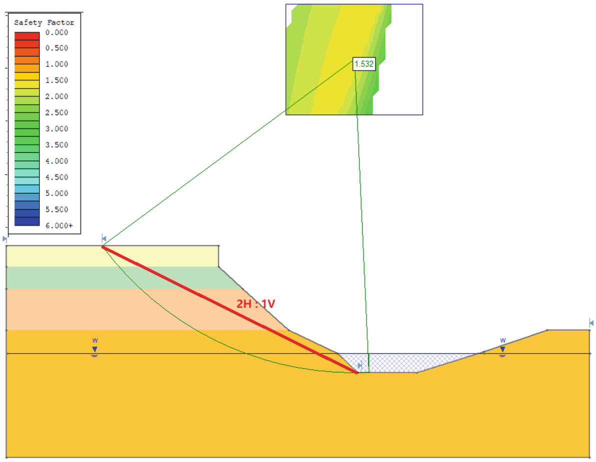
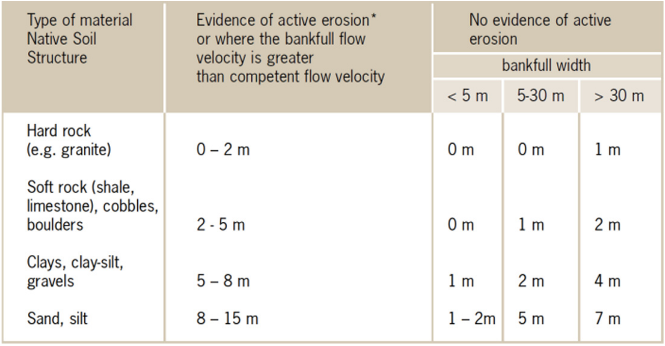


Fig. 14. Long-term stable slope back calculated, using Rocscience Software Slide 6.0, with inclination 2H: 1V (Analyzed by Ron Xia, 2015).

Table 1. Minimum toe erosion allowance – where river is within 15 m of slope toe (OMNR 2001).



Type of material Native Soil Structure	Evidence of active erosion* or where the bankfull flow velocity is greater than competent flow velocity	No evidence of active erosion		
		bankfull width		
		< 5 m	5-30 m	> 30 m
Hard rock (e.g. granite)	0 – 2 m	0 m	0 m	1 m
Soft rock (shale, limestone), cobbles, boulders	2 - 5 m	0 m	1 m	2 m
Clays, clay-silt, gravels	5 – 8 m	1 m	2 m	4 m
Sand, silt	8 – 15 m	1 – 2m	5 m	7 m

the research site, the river is within/less than 15 m from the toe. Active toe erosion is observed and slope sliding happened in the past two years. To the encountered silt to silt till with clayey/sandy matrix, trace of gravel, the expected erosion allowance would be in the range from 8–15 m, based on the information and conditions listed in the assessment Table from OMNR 2001.

3.3 Erosion Access Allowance

Erosion access allowance**,** or the setback needed is to ensure there's a large enough safety zone for people and vehicles to enter and exit an area during an emergency, such as a slope failure or flooding (OMNR 2001). By this way it provides a route for machinery to undertake periodic repairs as well as emergency vehicles.

The erosion access allowance is always applied in addition to the flooding hazard limit on river and stream systems and to ensure for: 1) available access during emergencies, 2) regular maintenance or repair failed structures and 3) protection from external events that affect an erosion prone area. The suggested minimum erosion allowance for river and stream systems should be minimum six (6) metres (OMNR 2001).

3.4 Long-Term Stable Top of Slope

Limit of long-term stable top of slope (LLTSTOS) can be calculated as the sum of toe erosion allowance, stable slope allowance and erosion access allowance, measured from the existing toe of a slope. Magnitude of each component, for the Thames River bank-slope at the study site, is summarized in Table 2.

Active erosion at the study site is noted and well documented (Brenk 2015; Brenk 2014; News Local 2009). Soil conditions at the toe of slope and the river bed adjacent to the toe of bank slope, is consisted of silt to silt till with sand/clay matrix and trace of gravel.

Considerable amount of soil at the slope toe is falling/sliding from upper zone of the slope in loose/soft and moist to wet conditions. Using Table 1, adopted from OMNR erosion assessment as a reference with our decades of practical experience, the expected toe-erosion allowance would be likely in the range from 8 to 15 m.

Slope is less of protection, no trees, no grasses, and no vegetation cover on the bank nearby the stream water. Plus the project site is located at the concave side of the tortuous-meanders river section. Current of lateral circular flow, from surface of water to bottom of riverbed, takes soil from the bank of concave side as sediment flow and makes deposit at convex side (Fig. 15).

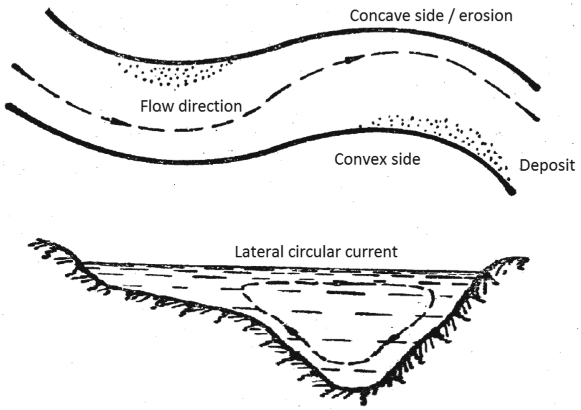


Fig. 15. Lateral circular current takes soil from concave side and deposits soil at convex side of river bank.

When the geometric sum of flow velocities, direct current and lateral current, is over/greater than the competent flow velocity, erosion will take place. Competent flow velocity v_c is the flow which the bed soil/material in the channel can sustain without erosion or scour, and it can be estimated as

$$v_c = cR^{\alpha} \tag{6}$$

Where c and α are coefficients regarding sediment deposit, soil type and erosion start up (Xu et al. 1990), R is hydraulic radius and defined as

$$R = \frac{A}{x} \tag{7}$$

Where A is the computed section area of discharge.
x is the wetting perimeter, and

$$x = b + 2h\sqrt{1 + m^2} \tag{8}$$

here b is the bottom width, h is the height of the bank submerged in water and m is the inclination of the bank slope.

The circular current is a core factor of creating erosion by under cutting. This is a common happened to all the tortuous meander rivers national and international (Xu et al. 1990). This particular is encountered at our study site and noticed during our site visiting. As a result, the most practical erosion allowance of 15 m set back should be anticipated and reasonable.

4 Lessons Learned

The OMNR Guideline provides tabulated toe erosion allowance ranges (Table 1) based on the soil type encountered at the respective location. The main criterion used in this estimation is the horizontal distance between the ‘edge of water’ and existing slope toe, or floodplain width.

For distances greater than 15 m, the Guideline provision is a zero for toe erosion allowance. In other words, it is considered that a slope whose toe is over 15 m away from the ‘edge of water’ would not be eroded in a time horizon of 100 years. It is therefore assumed that the average erosion rate of migration of the channel bed towards the respective bank is less than or equal to 0.15 m per year (Botzan 2011).

Building permit was issued in 1969 and in same year the house built up on top of the bank slope overlooking the Thames River. The couple of Shuttleworths bought the property and moved into the house at the year of 2001, which is about 32 years after, and their back yard was about 12 m deep if measured from the house to the top line of the bank slope (Brenk 2014).

Back calculation using the average erosion rate 0.15 m per year, the expected length of erosion within the past 32 years would be about 4.8 m. By this way, the original back yard could estimated as 4.8 + 12 = 16.8 m logically. Compare with the required total set back, the house is about 34 m beyond the boundary/limit of long-term stable top of slope (Table 2).

Table 2. The calculation of the long-term stable top of slope set back of the study project site.

Items	(m)
Toe erosion allowance	15
Stable slope allowance	30
Erosion access allowance	6
Limit of long-term stable top of slope	51

Frequently, the transition of toe-erosion making slope from unstable to collapse is very quietly, unnoticed until a significant proportion of soil mass from the bank slope has been removed. A large part of the rear yard collapses happened on 2009. The 40 ft deep back yard turned to 20 ft, lost about 50%. More importantly, erosion was continuing, the house is unsafe, and the couple moved out in 2012 with no choice. Again, a massive sliding happened on March 13 and 14, 2014, the house is condemned and reluctantly demolished on February 17, 2015 (Brenk 2015).

5 Conclusion

Generally, development should not occur on or on top of valley walls because the long-term stability of the slope, and therefore public health and safety, cannot be guaranteed. Development should be set back from the top of valley walls far enough to avoid increases in loading forces on the top of the slope, changes in drainage patterns that would compromise slope stability or exacerbate erosion of the slope face, and loss of stabilizing vegetation on the slope face (OMNR 2001).

Where the valley wall is over-steepened or subject to active toe erosion, development should be set farther back from the top of the valley wall so that the development will also be safe from erosion and slope failure in the long term (OMNR 2001).

The OMNR has developed a guideline to support the LTSTOS assessment. Three components introduced in the guideline are of interest in what the assessment of hazard limit is concerned: 1) toe erosion allowance, 2) stable slope allowance and 3) erosion access allowance.

Erosion access allowance provides a route for machinery to undertake periodic repairs as well as emergency vehicles. Geotechnical investigation and slope stability analysis against a Factor of Safety of minimum 1.5 are required to enable a review/issue permit of a hazard limit.

Protection structures, tress and vegetation covers always help to mitigate some hazards from toe erosion, surface downcutting/sheet erosion. Care must be taken to ensure the structures do not create new hazards and do not cause environmental damages or destroy natural systems that protect other areas.

Protection structures has to cost affordable; several pricey solutions were offered up by the municipality when it was first discovered that groundwater was causing the rapid erosion along the Thames. Unfortunately, cost of the protection construction and future maintenance could not afford by the property owners and the taxpayers and turning to the result of the house was demolished.

Hence, following the guideline of OMNR and the regulations of long-term stable top of slope (LTSTOS) assessment of local conservation authorities is a right/safe way to avoid an unexpected natural hazards/disaster of massive slope sliding.

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References

Botzan, T.: Lessons from application of environmental policies regulating development. In: Proceedings of 2011 Pan-Am CGS Geotechnical Conference, Toronto, Ontario, Canada (2011)
Brenk, D.V.: Couple's Battle with Township, County over Eroding Property Heads to Court. The London Free Press, News Local, London, Ontario (2015)
Brenk, D.V.: Home Sliding into Thames River. The London Free Press, News Local, London, Ontario (2014)
Canadian Geotechnical Society 2006: Canadian Foundation Engineering Manual, 4th edn, p. 195/488. The Canadian Geotechnical Society c/o Bitech Publishers Ltd. (2006)
Farouki, O.T.: Thermal Properties of Soils. U.S. Army CRREL Monograph 81-1, 136 p. (1981)
Hagerty, T.P., Kingston, M.S.: The Soils of Middlesex County, Volume 1. Report no. 56 of the Ontario Centre for Soil Resource Evaluation. Resources Management Branch of Ontario Ministry of Agriculture and Food, Guelph, Ontario (1992)
Hansen, M.: Photograph taken on Wednesday, April 17, 2013. The London Free Press/QMI Agency, London, Ontario (2013)
Ministry of the Environment and Ministry of Natural Resources 1975: Water Management Study for Thames River Basin, Province of Ontario, Canada (1975)
News Local 2009: Erosion Threatens Three Properties in Caradoc, Wednesday, June 10, 2009. News Local, London, Ontario (2009)
Nirupama, N., Simonovic, S.P.: Increase of flood risk due to urbanisation: a Canadian example. Nat. Hazards **40**, 25–41 (2007). https://doi.org/10.1007/s11069-006-0003-0
Ontario Ministry of Natural Resource 2001: Understanding Natural Hazards. Queen's Printer for Ontario. Printed in Ontario, Canada (2001)
Ontario Ministry of Natural Resources 2002: Technical Guide for River and Stream Systems: Erosion Hazard Limit, Province of Ontario, Canada (2002)
Patis, A.: No Solution for Owners of Condemned Homes. News.com, Blackburn (2014)
Statistics: Delaware, Ontario - The Weather Network (2015). www.theweathernetwork.com
Thames River Background Study Research Team 1998: The Thames River Watershed: A Background Study for Nomination under the Canadian Heritage Rivers System. The Upper Thames River Conservation Authority, London, Ontario, Canada (1998)
Thames River Implementation Committee 1975: Summary and Recommendations from the Thames River Basin Management Study. Thames River Implementation Committee (TRIC), London, Ontario (1975)
Toronto and Region Conservation Authority 2007: Planning and Development Procedural Manual. TRCA, Toronto, Ontario, Canada (2007)

Toronto and Region Conservation Authority 1994: Valley and Stream Corridor Management Program. TRCA, Toronto, Ontario, Canada (1994)

Upper Thames River Conservation Authority 1998: The Thames River Watershed, A Background Study for Nomination under the Canadian Heritage Rivers System. UTRCA, London, Ontario, Canada (1998)

Woo, M.K., Xia, Z.J.: Suprapermafrost groundwater seepage in gravelly terrain, Resolute, NWT, Canada. J. Permafrost Periglac. Process. **6**, 57–72 (1995a)

Woo, M.K., Xia, Z.J.: Effects of hydrology on the thermal conditions of the active layer. J. Nord. Hydrol. **27**, 129–142 (1995b)

Xia, Z.J., Xue, L., Shahine, J., Sun, Y.: Theoretical analysis of slope erosion. In: Proceedings of 55th Canadian Geotechnical Conference and 3rd Joint IAH and CGS Groundwater Conference, Niagara Falls, Ontario, Canada (2002)

Xia, Z.J., Woo, M.K., Chahine, J., Sun, Y.F.: Computation of frost table profile using Green Theorem. In: Proceedings of 54th Canadian Geotechnical Conference, 2nd Joint IAH and CGS Groundwater Conference, Calgary, Canada (2001)

Xia, Z.J.: A study of thermal cracks in frozen ground no. 3. In: Fourth International Symposium on Ground Freezing, Sapporo, 5–7 August 1985 (1985)

Xu, Y.Ch., Hu, D.B., Xue, C.Y.: Hydraulics, 3rd edn. Textbook of Dalian University of Science and Technology, Science Press, Beijing (1990)