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Stabilizing Coastal Slopes on the Great Lakes

Living With a Legacy

The Great Lakes Basin has a long history of shoreline and adjacent bluff changes with nearly 2 million years of glacial advance and retreat over ancient river valleys. When the glaciers receded about 10,000 years ago, mixtures of clay, silt, sand and rocks were left behind as layers of “glacial till” exposed in eroding bluffs and lakebeds. Within the till are layers of sand and gravel deposited as beaches and stream deltas at the borders of glacier and lake. There are also layers of sand, silt and clay deposited on the lake bottom when lake levels were much higher than they are today.

This geological legacy is important partly because soil types have different properties and differing resistance to erosion. Clay can stand as very steep slopes when dry only to fail as large landslides when wet or severely undercut. Sand is easily eroded but holds a more gentle slope and rarely fails catastrophically. Exposed bedrock is more resistant than clay or sand to erosion, but it eventually succumbs to the force of freezing and expanding of water within cracks, joints and porous layers, and the relentless attack of waves. The geological legacy is also important because of the presence or absence of natural defenses against breaking storm waves. Some properties have visible natural defenses in the form of broad, stable beaches or bedrock outcrops along the shore and invisible

defenses in the form of rock-armored lakebed, near-shore bars and shoals of sand, gravel or rock.

Additional geological factors contributing to erosion problems are the continuing flow of surface water and groundwater from the land, variable lake levels and storm activity on the lakes and potential climate change effects. These problems are a legacy of the climate and a natural result of close proximity to the dynamic watery margins of these very large bodies of water.

Another legacy of coastal property is the historic decision about where to put buildings. As soon as a building is sited on a coastal property with an eroding slope, the geological lifetime (geotime) of that building setback begins to be used up, and the “building use clock” starts ticking. Sometimes that “clock” ticks off the lifetime of the building. A setback is the distance that a building is set back from the edge of a slope or another defined line such as the high water line.

An existing building on an eroding shore has had its geotime reduced by the erosion that occurred since the building was built. Calculating the remaining geotime is simple if the average annual rate of erosion (recession rate) expected in the future can be estimated (Figure 1).

Landward relocation of a building resets the “building use clock” and restores value to the property.

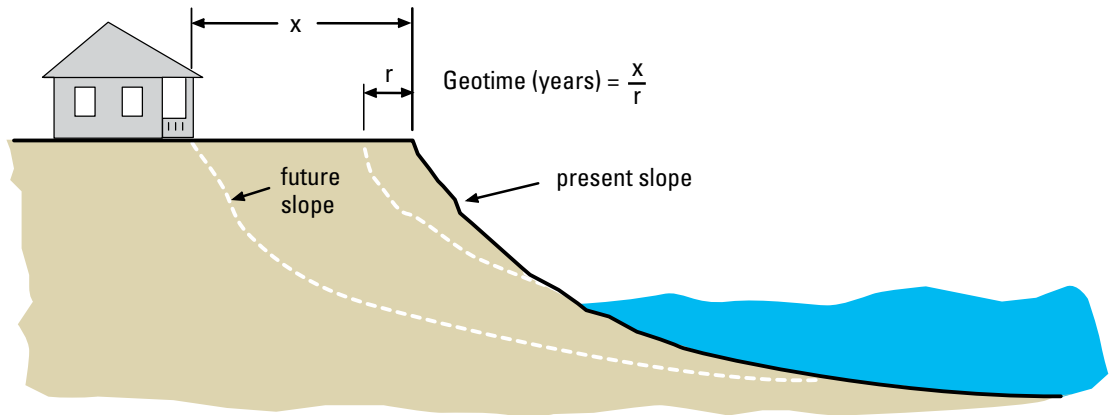


Figure 1: Geotime: The Lifetime of a Coastal Building in its Present Location

x = distance land can erode before the building is in danger of collapse
r = average amount per year of expected future recession

(ADAPTED FROM WORK BY KRIESEL, RANDALL AND LICHTKOPPLER 1993)

The Unseen Problem of Nearshore Lakebed Erosion

Erosion of the lakebed (also called lakebed downcutting) is common along cohesive shoreline banks and bluffs of glacial till and clay in the Great Lakes. In such locations, the rates at which visible erosion and recession of cohesive coastal slopes take place is ultimately controlled by the rates of invisible underwater erosion of the lakebed. Some of the bluff or bank slope recession takes place as a result of wave erosion at the toe of the slope. Where lakebed erosion occurs, it allows ever-larger waves to reach the toe of the slope (given the same water levels). Lakebed erosion and slope recession proceed in unison (Figure 2).

Where wave erosion occurs without lakebed erosion, a shallow platform of the uneroded lakebed is left as the coastal slope recedes. Waves dissipate their energy on this platform, reducing the ability of the waves to erode the toe of the slope.

Lakebed erosion also occurs on shorelines developed in relatively weak bedrock, such as shale and some sandstone.

Lakebed erosion is an irreversible process. Eroded nearshore lakebed areas are not naturally restored in the way sandy beaches may be when sand transported offshore during storms is brought onshore again. Fine sediments in the glacial tills, clays or shales are not stable on the beach and nearshore waters and are kept in suspension by wave action until they settle out in the deep water of the lake basins.

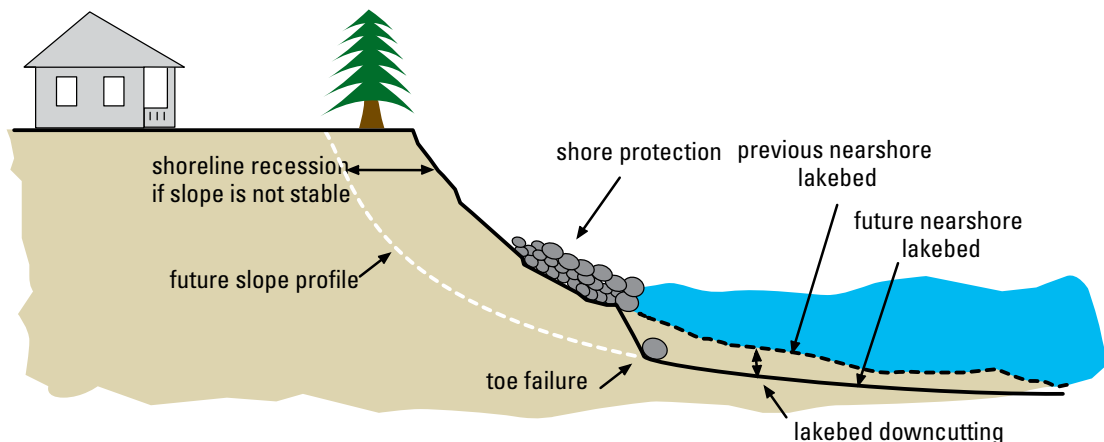


Figure 2: Lakebed Erosion With Slope Recession and Failure of Shore Protection Structure

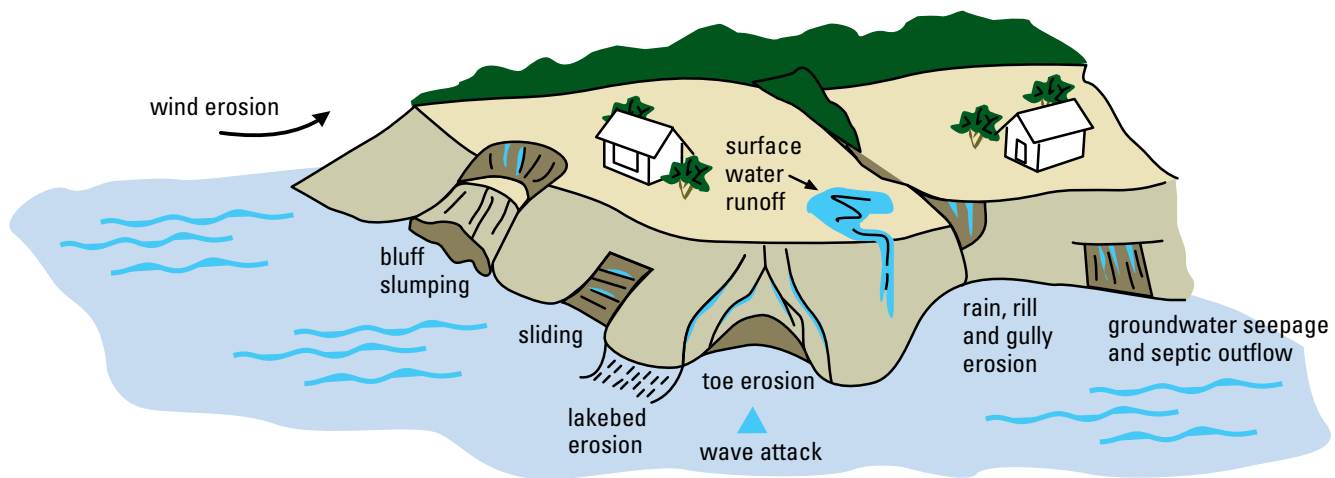


Figure 3: Causes and Effects of Coastal Erosion

Measurements indicate rates of vertical lakebed erosion in the range of 0.4 to 6.0 inches per year (1–15 cm/year). More typical erosion rates are 1.2 to 2.0 inches per year (3-5 cm/year). Lakebed erosion rates tend to be highest close to shore where breaking waves cause much turbulence. The erosion rates tend to decrease offshore to just a few tenths of an inch per year (a few millimeters per year) in water depths greater than six feet (a few meters). Lakebed erosion proceeds slowly and steadily, usually only a few tenths of an inch (millimeters) at a time, but it occurs throughout the year and may extend into water depths greater than 33 feet (10 meters).

The rate of vertical erosion at a point on a nearshore profile can usually be predicted from the profile slope—the steeper the slope, the greater the erosion rate. Most cohesive profiles with steep slopes close to shore develop a concave shape where erosion rates are highest, with the slope decreasing offshore into deeper water as erosion rates decrease (Figure 2). In areas where bedrock occurs in shallow water, or there is an accumulation of cobbles and boulders forming a protective lag deposit over the cohesive sediments, a nearly horizontal platform will develop, and this platform will ultimately reduce the ability of the waves to erode the toe of the slope.

Lakebed erosion creates future unpleasant surprises for coastal property owners. In many places that don't have lakebed erosion, erosion of the bluff toe and the beach platform decreases during periods of low lake levels and increases during high lake levels. The opposite effect due to lake-level changes occurs where the nearshore lakebed is eroding.

During periods of low lake levels, the lake bed is subjected to higher currents due to wave motion, and the zone of wave breaking where erosion is highest occurs farther

offshore. As a result, when high water levels return, the water depth close to shore is greater than it was during the previous time of the same high water levels—increasing the wave impact and creating more toe erosion on the coastal slope.

Lakebed erosion undermines the foundations of shore protection structures and subjects these structures to greater wave energy when higher lake levels and storms return. Lakebed erosion is one cause of unexpectedly short useful lives of many shore protection structures.

Many eroding coastal slopes contain material that contributes to lakebed erosion. Sand and gravel eroded from these slopes move along the shore and nearshore by wave and current action. These abrasive materials may form a veneer on a narrow beach and on the lakebed overlying the cohesive material. A thin cover of sand and gravel on the lakebed increases the rate at which erosion takes place through abrasion and the impact of the sediment particles, compared to the rate of erosion where abrasive materials are not present. Lakebed erosion is a continuing process as even small waves and slight currents move the particles across the erodible surfaces. Erosion during storms can occur even where the sand is thick because of the migration of features such as troughs located landward of sand bars.

If sufficient sand and gravel accumulate and remain in place, the resulting deposit can protect the underlying lake bed from erosion. In some locations, sand and gravel deposits move along shore until they are deposited to form spits, bars, troughs and dune deposits. In one situation, lakebed erosion decreased where there were sand thicknesses greater than six inches (15 cm). Because of the migration of sand bars over a number of years, it probably takes more than 20 inches (50 cm) of sand to protect the lakebed from erosion.



Where cohesive lakebed material seems resistant to erosion due to clay cohesion or over-consolidation of glacial tills, this strength can greatly decrease over time as cohesive material on the surface of the lakebed loses strength. The softened, weathered cohesive layer on the lakebed is easily removed even by relatively small waves.

Coastal Slope Stability and Instability

Erosion and instability of coastal slopes is a multifaceted problem, as shown in Figure 3. All of the facets of an erosion problem may not be apparent during a casual visit.

Slopes fail when forces of gravity acting on soil masses become stronger than the soil forces resisting gravity. This tug-of-war takes place at tiny soil grain boundaries and along large surfaces called potential failure planes within soil masses. Cohesion is the term for soil strength between particles. Shear strength is the resistance of soil to failure along potential failure surfaces (Figure 4).

Coastal bluff erosion can be unpredictable. Bluff-top land and coastal slopes may not have changed significantly in the past 10 years, yet they may lose 5–50 feet in a single landslide event next week, or next year. Owners of some coastal properties along low-lying sandy terraces on Wisconsin’s Lake Michigan shore were surprised when 30–50 feet (10–15 meters) of their front yards disappeared in a weekend storm in 1985.

Slope conditions (like slope properties) create slope instability. These conditions include surface water moving

into the ground through fractures in clay layers or water seeping through sand layers and lenses (non-continuous layers, pockets of sand) behind the slope face. Other conditions that influence slope stability and instability are the amount, type and condition of vegetative cover; the presence and route taken by surface water moving from the land to the lake; and the weathering of soil and rock on the slope surface. Potential failure surfaces may lie hidden deep within a slope where the balance of forces can shift, determining the fate of the slope.

Landslide-triggering mechanisms on slopes include:

- Intense rainfall
- Rapid snowmelt
- Wave or current-induced erosion of the lower parts of the slope and in the lakebed
- Rapid drop in external water level (for partially submerged slopes)
- Rapid rise in groundwater within a slope
- Earth shaking from human-induced vibrations or earthquakes

Overly steepened slopes, groundwater that rises behind a slope and seeps out, and soaking of the soils by rainwater or other sources of surface water all change the balance of the forces and may lead to slope failure.

Water on the Land

Water that exceeds the amount needed to keep slope vegetation healthy is a threat to slope stability. Water works as a force, a load and a lubricant in promoting soil failure.

Some surface-water runoff and groundwater originates on coastal property. Surface water and groundwater also pass through the coastal property on the way to the lake from inland sources.

Surface-water runoff

Surface runoff over the face of a coastal slope gradually loosens and visibly removes exposed soil on the slope, accounting for up to half of the loss of slope soils in some places. The effects on slope face erosion are most prominent where the slope soils are highly erodible and large surface areas are exposed.

Factors that control surface-water runoff include:

- Slope of land surfaces. Water runs off steeply sloped land faster than off gently sloped land.
- Water quantity and rate of application—the volume of rain water, snow melt or artificially discharged water (from human influences) available and the rate at which it arrives on the ground surface.
- The characteristics of land surfaces. Surface runoff from grass lawns is greater than runoff from grass lands and can be almost as great as runoff from paved areas. Surfaces that are highly permeable and allow water to easily penetrate the soil result in less surface runoff and more groundwater infiltration.
- The presence or absence of depressions in the land on the face of the coastal bank or bluff that channel water into erosive streams on the slope.

Indicators of surface-water problems include:

- Exposed soil surfaces on bank and bluff slopes, from miniature trench-like rills to large gullies.
- Exposed lengths of drain pipe or foundations of stairways or other structures on slopes.

Groundwater: a hidden threat

Invisible groundwater can be more dangerous than visible surface-water runoff. Groundwater can trigger large, deep landslides that sometimes have catastrophic consequences. The presence of water in soil pores and soil fractures beneath a slope weakens the soil by adding weight and reducing the frictional resistance among soil particles that are in contact with one another.

Water Arrives on the Land in Two Ways

- Surface-water runoff comes from rain water, snow melt, groundwater seeps or springs, and lawn or garden sprinkling systems. The runoff may come from roofs through gutter pipes or from driveways, parking lots and roads.
- Groundwater infiltrates into coastal soil and moves to a coastal slope face from any of the above sources, from septic systems, dry wells or springs.

Visible Indicators of Erosion and Slope Instability

A site visit by a coastal processes professional can find signs of past and present erosion and slope instability. Common visible indicators include the following (adapted from Ontario 2001):

- Bare slope surfaces. Evidence that erosion is too rapid for plant growth to be established.
- Lumpy, uneven surfaces on the slope. Indication of past earth movement, or ongoing soil creep.
- Bare vertical or near-vertical faces on a vegetated slope.
- Evidence of slumping activity.
- Springs, seeping water and bands of vegetation common to wet soil. Evidence of a saturated soil layer within the slope that makes the slope above the layer susceptible to failure.
- Soil cracks and separations on the slope and on the land near the slope. An indication of possible slow mass movement and potential future slumping.
- An undercut slope base with a steep or vertical face.
- Indication of an unstable slope condition and a potential future slide or slump in the slope above the steep face.
- Shore protection structure tipped lakeward. Indication of possible movement of the base of the slope behind the structure and a future mass movement of slope soil, or undermining of the structure due to lakebed erosion.
- Presence of a mass of soil at the base of the slope and a curved bare earth face on the slope. Evidence of a recent slope failure.

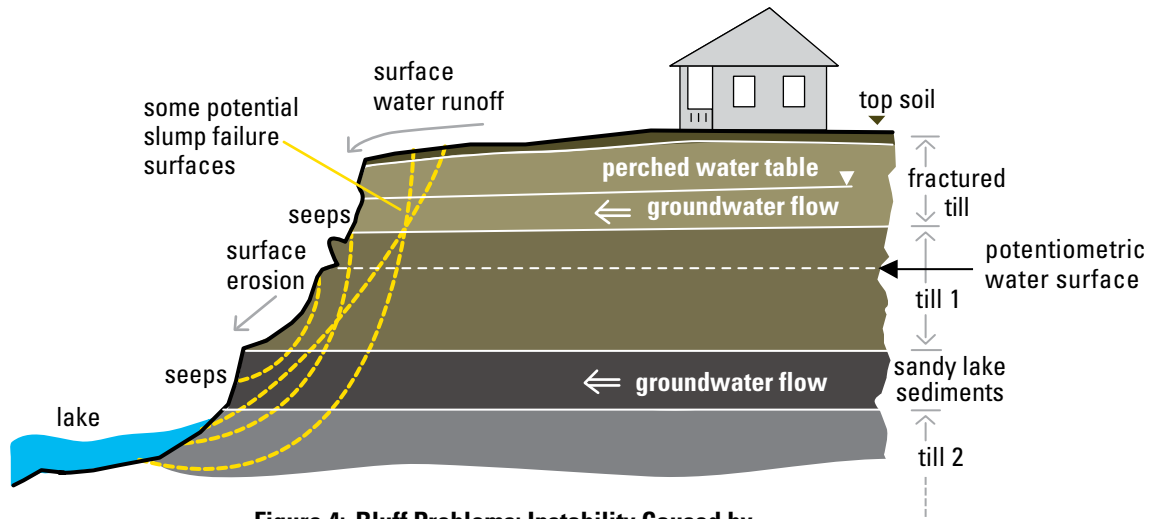


Figure 4: Bluff Problems: Instability Caused by Surface-Water Runoff and Groundwater Seepage

All coastal properties have groundwater flow beneath them (Figure 4). The ground adjacent to and lower than the lake surface elevation will generally be saturated. On sandy shores, the upper surface of this zone of saturation (called the water table) is at lake level at the shoreline and rises gradually in the inland direction. Groundwater at and below this primary water table contributes to slope movements only if failure surfaces (slip surfaces) extend close to, or below, lake level. For slopes of only sand and/or gravel, the primary water table will be the only groundwater flow system present. On such porous banks, infiltrating water moves directly into the lake-level groundwater flow system and causes little weakening of the soil.

Many coastal bluffs contain soil layers called aquitards that retard water flow into the water table near lake level. Clay soils and glacial till soils have this retarding characteristic. Coastal landslide problems develop primarily where there are zones of water saturation above the lower, main water table—perched groundwater tables (Figures 4 and 5).

A perched water table is water at an elevation above the elevation of the main water table. The higher elevation of a perched water table is caused by resistance of lower bluff soils to the downward and lakeward movement of water through the fractured till layer. Groundwater also flows lakeward within the sandy layer. The main water table surface (potentiometric water surface) shown within the till 1 layer is the elevation to which groundwater flowing in the sandy lake sediment layer below would rise if vertical holes were drilled from the bluff top to the sandy layer. Except when the slope face is frozen, the water surfaces

within the bluff would slope downward near the slope face: a feature not shown in Figures 4 and 5.

At sites with perched groundwater, groundwater collects in the sand and gravel layers (aquifers) because underlying soil layers resistant to flow prevent downward movement of the water. The principal direction of water flow in these sand and gravel layers is outward toward the slope face where the water emerges in the form of seeps or springs.

Factors that control groundwater influence on slope stability include:

- The quantity and distribution of groundwater beneath coastal property.
- The amount and rate of water infiltration into coastal soils. The greatest infiltration comes from prolonged, slow application of water at infiltration locations.
- The soil moisture content.
- The ability of water to move through the soil.
- Soil texture, structure and mineralogy, including fracture patterns in clay soils.

The structure of the soil is controlled by the properties and distributions of soil layers. Two of these properties are porosity and permeability. Porosity is the percentage of the total volume of a soil that is occupied by air or water but not by solid particles. Porosity determines the water storage capacity in soil. Permeability is a measure of the ability of water to flow through soil, rock or other material.

Indicators That a Property Might Contain Perched Groundwater and be Vulnerable to Water-Induced Landslides

- Clay, flow-resistant layers (aquifers) located between the bluff top and the beach level.
- Wetlands near, or on, the property.
- Areas of decayed vegetation in low areas.
- Exposed soil surfaces on the land.
- Seeps or flowing springs emerging from the bluff or bank face.
- Indications of perched ground water in driller's log books for water wells.
- Presence of vegetation that requires abundant soil moisture.
- Land near the top of the slope that is at a slightly lower elevation than the adjoining land surface.
- Trees and large shrubs leaning toward the lake.
- Linear shoreline-parallel "wrinkles" in grassy slopes, indicating slow soil creep down the slope.

Water readily flows through sand, gravel and fractured glacial till layers. Water flows with great difficulty through unfractured till and layers of very fine silt and clay sediments that had been deposited in ancient lake deposits. Where the glacial environments of soil deposition were complex, or where soil layers have already been subjected to slow landslide activity, the distribution of layers slightly resistant to flow and layers highly resistant to flow can be complex.

Groundwater problems are most severe in times of greatest infiltration. Expect a bluff to be least stable during times of heavy precipitation or thawing of significant snow cover. Water tables can rise temporarily from several feet to tens of feet in a few days to a few weeks following a single intense rainfall. Where perched groundwater normally moves outward on to the bluff face, significant water storage within a bluff can develop during cold periods when freezing of the surface soil temporarily blocks groundwater discharge at seeps or springs on the slope face.

Bluff movements tend to follow seasonal cycles. Rates of movement tend to increase with late fall storms and the beginning of bluff surface freezing. At these times, precipitation and storm wave activity increase, and a frozen bluff face causes a backup of the groundwater into vulnerable perched aquifers. More rapid bluff movements continue

through the winter while perched water tables remain high. Movement continues into the spring through spring rains, rapid snow melt, and bluff-face thawing that releases the excess perched groundwater through soil weakened by winter's soil freeze-thaw activity. Groundwater activity and bluff movements tend to persist at somewhat lower rates during prolonged periods of little storm wave activity and periods of low lake levels.

Exposed soil surfaces on the land indicate easy infiltration into the groundwater. Seeps or flowing springs emerging from the bluff or bank face indicate that perched zones of groundwater saturation are discharging from the slope. During periods of heavy discharge, these seeps and springs can organize into stream channels that cause significant surface erosion. Standing water in wetlands is probably capable of leaking into the underlying groundwater flow system. Slope vegetation that requires abundant soil moisture suggests the presence of seeps or springs that are not visible during a temporary dry spell. Areas of decayed vegetation in low areas on the land indicate possible prolonged periods of standing water that may have infiltrated into the groundwater, rather than evaporating.

There are some invisible indicators of perched groundwater in a coastal slope. Flow-resistant layers within a slope are best identified by drilling test holes and recording the depths of changes in soil properties. A cheaper (and less conclusive) alternative is mapping undisturbed soil conditions on the bluff face and assuming that these observed conditions extend under the property. Geophysical tests are needed to determine soil profiles and properties. A thorough examination requires analysis of samples from the slope and test holes. Although an irregular distribution of glacial soils may complicate the groundwater situation, drilling logs from wells on neighboring properties can be a valuable indicator.

Managing Water on the Land

Surface-water management

Surface-water management is a first line of defense for safeguarding slope stability (Figure 5). Here are some steps for surface-water management on a coastal property and coastal slope:

- Eliminate surface-water runoff from the land, over the edge and down the face of a slope. This can be done by grading or re-grading the land with a modest berm near the edge of the bluff, re-sloping the land away from the edge of the bank and bluff, and/or collecting runoff in a storm sewer or in a private drain pipe that can be run down the slope to the lake in a way that does not worsen surface erosion on the slope.

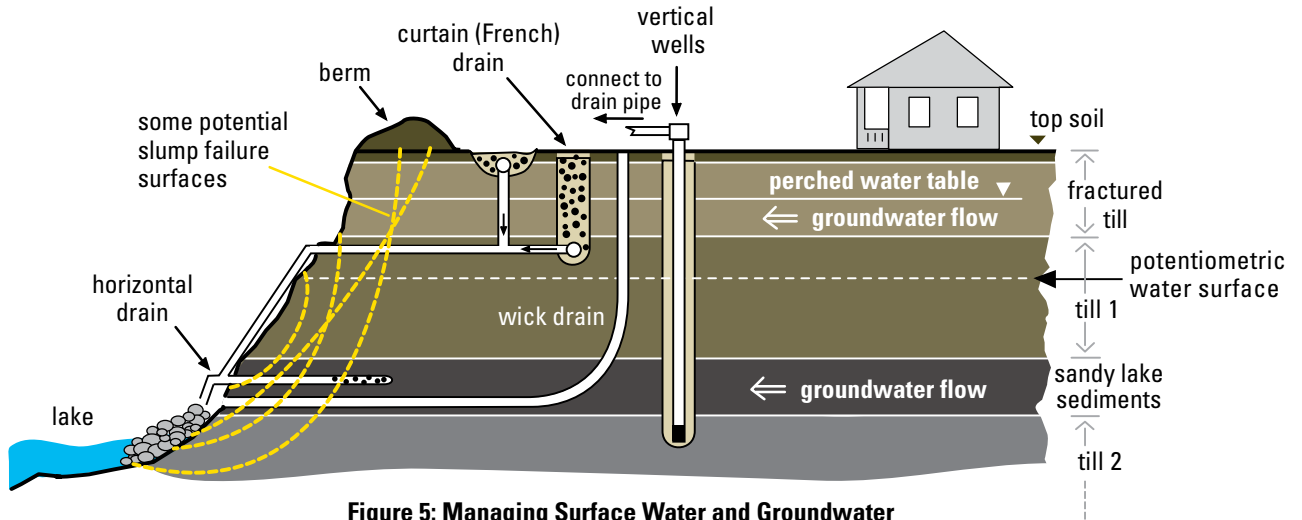


Figure 5: Managing Surface Water and Groundwater

- Slope and drain large drainage surfaces (such as mowed lawns, paved roads, driveways, tennis courts and roofs of buildings) to storm sewers or private drain pipes to minimize drainage onto coastal slopes and minimize ponding that may contribute these surface waters to the perched groundwater flowing beneath the land surface and toward the coastal slope. A tile drainage system can be installed beneath a lawn to collect infiltrating groundwater and move it in pipes or tubes away from the property, inland or down the bluff face. Too much drainage can hinder vegetation survival.
- Avoid creating tilled gardens and flower beds of significant size near coastal slopes. These areas may become significant recharge areas for surface water to move into the groundwater flowing within the coastal land towards the slope. The significance of size is a matter of professional judgment for a consultant.
- Plant small trees, shrubs, grasses or other ground cover plants on and near coastal slopes. Surface water and shallow groundwater is removed from the soil by transpiration (“exhaling” moisture) through plants.
- Surface-water runoff from seeps or springs should be diverted from the slope, collected and drained through drain pipes mentioned above. Once vegetation becomes well-established on the slope, this measure may become unnecessary except in extreme precipitation events.

- Decrease the velocity of water flowing across coastal land in gullies to reduce the erosive scour potential of this surface water runoff. Professional help may be needed to minimize ponding and introduction of this water to the groundwater flow beneath the property.

Groundwater management

Groundwater management is a second line of defense against slope instability. The best management technique is to minimize the amount of water in the ground. Most critical is the removal of water from perched zones of saturation that are beneath the property near the coastal slope and slope face in the critical zone of soil volume where future landslides could be initiated (Figure 5).

Not all groundwater need be removed. Only that amount of excess water that could possibly cause soil instability needs removing to make a coastal slope and property stable following future extreme precipitation events and extreme groundwater conditions. Too much groundwater removal may not allow deep-rooted vegetation to establish and thrive on the land and on coastal slopes.

While some of these surface-water control strategies can be implemented by a competent do-it-yourself-type of property owner, professional advice and judgment are often needed to anticipate how severe extreme precipitation events may be, how serious groundwater conditions may become, how much groundwater to remove, where to remove it and how to drain it away harmlessly.

Here are some general ways to manage groundwater flowing beneath a coastal property and toward a coastal slope:

- Correct problems with slope seepage from septic systems. If hook-up to a community sewer system is not possible, septic systems should have leach fields located as far from the coastal slope as possible with discharge directed away from the coast. Potential contamination of water supply wells is an overriding concern in leach field location.
- Intercept perched groundwater flowing beneath the property and toward the coastal slope. Interception should be to a depth below the deepest of the potential failure or slip surfaces over which the slope (or portions of the slope) could slide. This action drains water from the critical zone of soil in which potential future landslide failure surfaces (slip surfaces) are located.

Figure 5 shows a number of ways for controlling groundwater. Interceptor drain systems may be trench drains (French drains, geocomposite drains) dug roughly parallel to and an adequate distance landward of the coastal slope edge.

Interception of water may be done with a series of vertical pumped wells or relief wells. Vertical wells are normally recommended where the slope to be dewatered has already experienced downslope movement. Trenches and wells must be landward of the most landward possible slope failure surface.

Interception can also be done by drilling short nearly horizontal drains into the water-bearing soil layers behind the slope from the face of the slope. Water in the perched aquifer layers within the critical zone beneath the slope drain by gravity, discharging down the bluff face through pipes or tubes. Horizontal drains are favored by most slope engineers because of their mechanical simplicity. If a bluff is already experiencing significant slump displacement, horizontal drains can become distorted, damaged and ineffective if the movement persists.

A relatively new method for groundwater management is the installation of wick drains. Wick drains are flat corrugated pieces of plastic (approximately four-inches-wide and half-an-inch-thick) covered with water-permeable geotextile. The wick drains are placed in a parabolic shape from the top of the slope down through the water-bearing soil layers. The drains exit the slope near the bluff toe-beach interface.

Wick drains are installed using directional drilling equipment placed at the top of the slope and positioned to intercept the water-bearing layers. A row of wick drains are typically installed parallel to the bluff edge.

Under no circumstances construct any dewatering or water channeling system without consulting a professional with experience in solving groundwater problems and in meeting environmental regulations.

The Importance of Groundwater Management

A Wisconsin property on Lake Michigan has an eroding bluff that is 100 feet high. The present slope is 2:1 (horizontal:vertical distances). The house is located just 100 feet from the edge of the bluff (Figure 6).

An analysis of the situation by a slope stability expert indicates:

- a stable slope ratio of 3.7:1 (horizontal:vertical distance) because of a potential for a lot of groundwater in the bluff.
- dewatering of the property behind the slope could reduce that stable slope ratio to 2.6:1.

The first piece of information is not good news: the stable edge of the present bluff "as is" would be: $(3.7 - 2.0) \times 100$ feet = 170 feet from the existing bluff edge, assuming that the toe of the bluff remains stable and there is a lot of groundwater in the bluff. At least part of the house is located on this potentially unstable land near the present bluff edge.

The second piece of information is better news: the stable edge of the bluff with effective dewatering would be: $(2.6 - 2.0) \times 100$ feet = 60 feet. The house is located 40 feet landward of the estimated new stable edge of the bluff, if dewatering takes place and the toe of the bluff can be made stable.

The Problems of Soil Creep

Most visible forms of slope failures are due to shallow translational sliding of soil down a slope or deeper rotational failures of large blocks of cohesive soil on a slope. In some coastal slopes, there is a much smaller and slower lakeward and down slope movement of soil known as plastic creep movement or plastic creep deformation.

These creep movements may be continuous or intermittent, starting and stopping in cycles. These movements can occur in certain soils under stresses and forces that are less than those that cause abrupt slope failure. Creep may occur in an intact slope, within an unstable slump block, or within a failed surface layer on a slope. Creep may cause structural damage to drainage systems within slopes and other structures (like stairways) on slopes. In the long term, creep may threaten the stability of buildings located close to the edges of coastal slopes.

In other situations, creep may be of little concern and can be tolerated. See Forrester (2000) for more information on plastic creep. Improved drainage of surface and

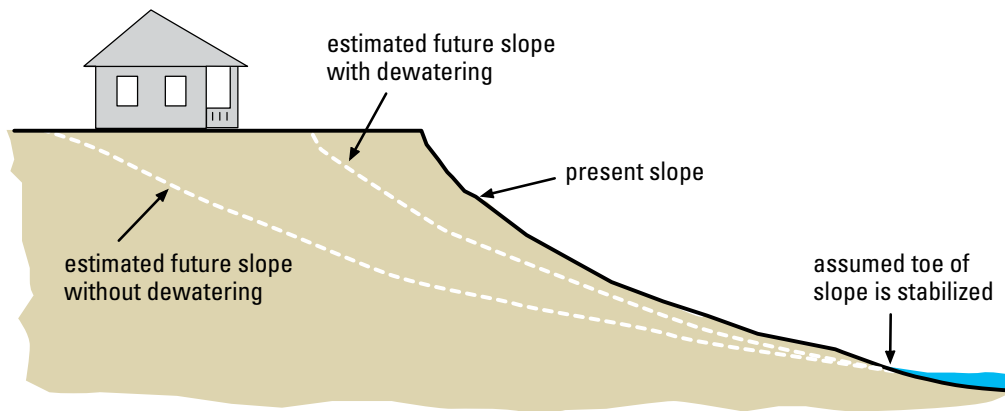


Figure 6: Slope Stability With and Without Dewatering

groundwater may not be adequate to completely stop creep. Some form of restraining structure may also be needed. Slope stability experts can test slopes for the presence and magnitude of creep movements. Engineers with local and county governments and state highway departments are good sources to contact to see if plastic creep movements are a problem on roadway slopes and other slopes on government property in the area.

Prevention of soil creep may require re-grading to much gentler slopes than needed where creep is not present. Creep is a common problem along Wisconsin's Douglas County and Bayfield County coasts on the Bayfield Peninsula of Lake Superior. At one location near Port Wing, the U.S. Army Corps of Engineers re-graded an eroding slope to a 5:1 (horizontal:vertical) slope, vegetated the slope, and installed a field stone revetment and timber seawall as shore protection at the base of the slope. This shore protection system remains intact many years after installation in 1978 and 1979. In contrast, many slopes along Wisconsin's Lake Michigan shore, at locations where creep is not present, have been re-graded to a steeper, 2.5:1 slope and vegetated with shore protection constructed at the toe of the slope.

Improving Slope Stability

There are three basic slope stabilization strategies (Figure 7). Planting vegetation is the simplest strategy. Constructing toe protection is the most complex and problematic strategy. Toe protection is discussed in the *Living on the Coast*, the 2003 Sea Grant booklet. Coastal slopes can be reshaped to improve stability if there is sufficient space between buildings (or proposed buildings) and the edges of coastal slopes.

Slope stabilization options include the following approaches:

- Cutback slope (Figure 8)
- Cut-and-fill slope (Figure 9)
- Terraced slope (Figure 10)
- Filled slope (Figure 11)

Each of these approaches requires that the toes of these slopes are stable. At coastal sites lacking non-eroding bedrock and broad, stable beaches, shore protection structures may be a necessary element in a slope stabilization plan. Sources of information about shore protection structures are listed in the reference section at the end of this pamphlet.

Check with regulatory agencies to learn what slope modification options are allowable. The cut and fill, and fill slope methods may not be allowed where the desired method requires encroachment on the lakebed. The terraced slope approach involves construction of bulkheads to increase the slope's resistance to sliding. Check with coastal engineers or geologists to learn the pros and cons of each option. Check with contractors to determine their experience in slope modification.

Using Vegetation to Improve Slope Stability

Woody vegetation has many beneficial effects on slope stability (Figure 12). Leaves intercept rain drops, causing absorption and evaporation of moisture and reducing the amount available for infiltration into the slope soils. Roots extract some of the moisture that sinks into

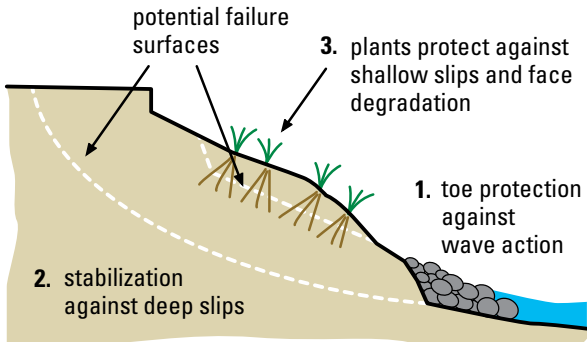


Figure 7: Three Basic Bluff Stabilization Strategies

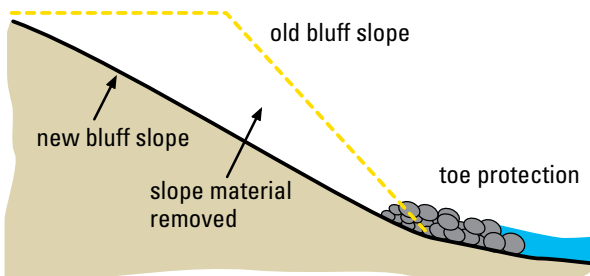


Figure 8: Cutback Slope Stabilization Method

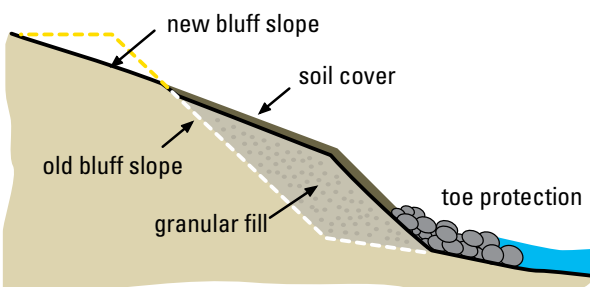


Figure 9: Cut and Fill Slope Stabilization Method

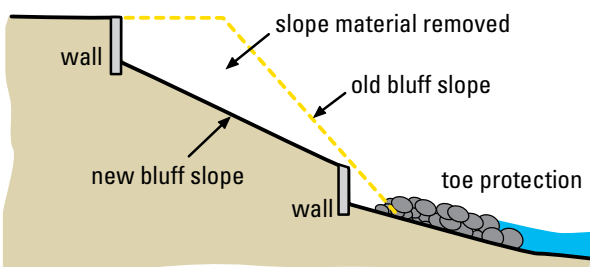


Figure 10: Terraced Bluff Stabilization Method

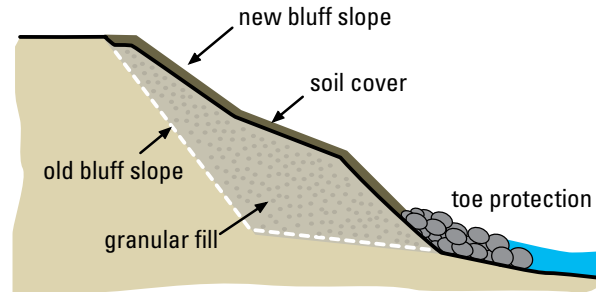


Figure 11: Fill Slope Stabilization Method

the soil, transferring it to leaves where it is lost to the atmosphere by the biological process of transpiration (“exhaling” moisture). At the same time, roots reinforce the soil, adding shear strength as they penetrate deeper and deeper into the slope. Deep roots of trees and shrubs anchor themselves into firm slope layers, providing structural support to the soils upslope of the roots. Roots help bind soil masses within which they are enmeshed. Stems and trapped surface detritus from decaying leaves slow down slope movement of surface water.

However, woody vegetation can also have negative effects on slope stability. Roots and stems increase the roughness of the slope surface, making the soil more permeable and allowing for more water infiltration. Depletion of soil moisture taken up by the roots of plants may cause greater drying of slope soils and formation of desiccation cracks that cause more soil infiltration. The weight of large trees on a slope creates positive, stabilizing loads perpendicular to the slope surface and negative, destabilizing down-slope loads parallel to the slope surface. Trees with large areas exposed to the wind transmit this dynamic force through the root systems to the slope. Plants do not grow readily on moving slopes, and the roots seldom penetrate deeply enough to stabilize slumping soil.

Some of the negative effects of woody vegetation can be reduced. For example, low shrubs (with low weight) can be planted on upper slopes, and tall trees can be limited to lower slopes where their high weights and high root masses are most beneficial and least detrimental. This ordering has a second benefit in improving lake views from the bluff top. Some species of trees on upper and intermediate slopes can be cut in a pruning process called coppicing that removes most of the weight but preserves the living root system. Once cut, these trees and bushes produce more roots that further strengthen the slope. These species include many northern hardwoods, willows and aspen.

Picking Safe Setback Distances in Constructing Buildings Near Coastal Slopes

Uncertainty about soil properties, past and future erosion (recession) rates and past and future soil conditions can have a large effect on the safe setback distance for construction on land behind the top edge of coastal slopes. Property owners are advised to consult with their local planning and zoning office to see if setback ordinances have been adopted for their counties.

Shore Protection Structures

Many bluffs and banks depend upon shore protection structures to maintain the stability of the toe and lower face of the slope. The adequacy and durability of such shore protection structures add an element of uncertainty to many efforts to achieve slope stability.

Great Lakes shore property owners have accumulated a century of experience with shore protection structures as

aids to the stabilization of eroding property. This history is littered with many failed structures and structures with useful lives much shorter than anticipated. In places where the lakebed is eroding, most types of shore protection structures will eventually be seriously undermined to the point of collapse. Freeze-thaw expansion and cracking of armor stone can greatly shorten the usefulness of many riprap revetments.

Minimum design guidelines for shore protection structures are no longer available to the public. Expert advice is needed to determine slope stability and the expected performance of shore protection structures. More information on shore protection structures can be found in the reference section at the end of this pamphlet.

Anticipate Changes in Climate

Although natural regional and local climate changes occur, a global warming trend appears to be continuing. Some climate changes have a major influence on the stability of coastal slopes—changes in the frequency and intensity of major precipitation events, changes in the

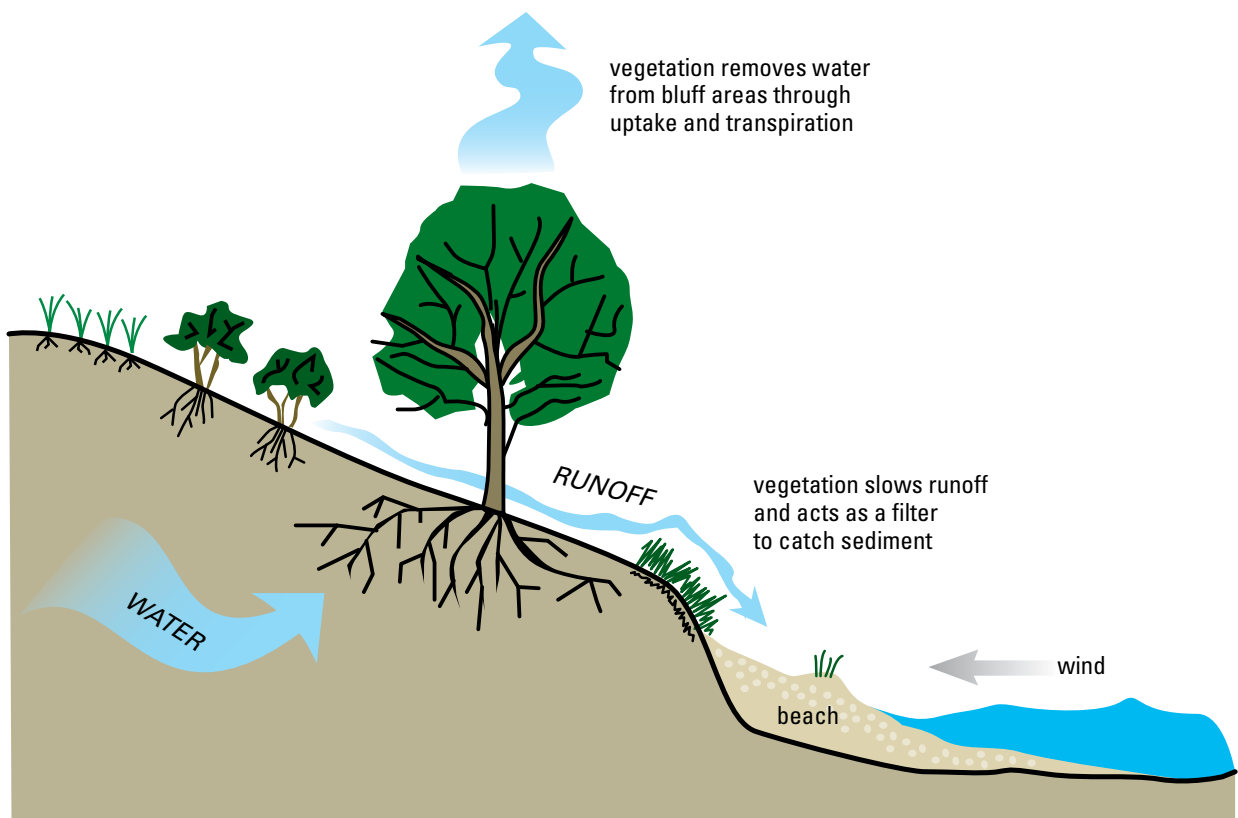


Figure 12: Revegetated Coastal Slope



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length and extent of frozen ground conditions, changes in the number of freeze-thaw cycles during the winter, changes in lake levels, and changes in the frequency and intensity of storm waves. For example, more frequent periods of winter thawing will contribute to more episodes of massive soil failures in coastal bluffs.

Anticipation and adaptation are two related options suggested for coastal property owners in preparing for climate change. They should anticipate more and greater extremes of weather than in the past and locate new buildings farther from the shore than the recent history of coastal response to natural processes would indicate. They should also choose slope stabilization measures that can be modified to adapt to changing climate conditions as they develop.

Being Vigilant to Nearby Land Development

Surface and groundwater problems on coastal property are frequently local indications of much larger problems that affect multiple land owners. Monitor changes in land development occurring landward and adjacent to the property. There are no rules of thumb for estimating how far the impacts of significant development will be felt.

Construction and reconstruction of roads, ditches, sewer lines, homes, commercial buildings, industrial plants and

other structures can alter surface and groundwater flow to the detriment of coastal slope stability. Contact the developer responsible for the project and the government agency that regulates the development to express your concerns and to seek analysis by slope stability experts and changes in proposed surface water and groundwater management.

More on Slope Instability

Some coastal slopes are closer than others to sudden failure. The perceived state of stability against future sliding or slumping is commonly expressed as a factor of safety (or safety factor).

Factor of safety

Every soil has a maximum capacity to resist shearing failure. This capacity is referred to as the shear strength of the soil. A factor of safety is the ratio of shear strength to shear stress from the forces that are pulling the mass downward. A factor of safety greater than one is good because it means that the forces resisting failure of the slope are stronger than the forces promoting failure. Once the balance of forces (factor of safety) is reduced to one (equality) or less than one, slope failure is likely to occur.

A few words of caution about factors of safety: The adequacy of a factor of safety depends upon the assumptions made while choosing values to represent soil conditions

What Does Factor of Safety Mean?

As an example, take a factor of safety equal to 1.1 for a particular potential failure surface deep within a given coastal slope on your property:

Factor of safety = forces resisting failure = shear strength forces promoting failure shear stress = 1.1 (in this example)

In this situation, the forces resisting failure along that potential failure surface are just 10 percent greater than the forces promoting failure along that surface. The shear strength of the soil along that potential failure surface is 10 percent greater than the shear stress within the soil along that surface.

A consultant might say that it is his or her professional opinion, based on this information, that the slope is likely to fail along this particular surface if these forces or shear stress change or if the soil strength is not as great as assumed or measured.

Design Minimum Factors of Safety for Coastal Slopes in Ontario

LAND USE	DESIGN MINIMUM FACTOR OF SAFETY
Passive. No buildings near slope; fields, woods, forest, etc.	1.1
Light. No habitable structures near slope, recreational parks, golf courses, barns, garages, swimming pools, sheds, buried small utilities, gazebos, satellite dishes, dog houses, etc.	1.2 – 1.3
Active. Habitable or occupied structures near slope, residential, commercial, industrial buildings, retaining walls, etc.	1.3 – 1.5
Public Use. Structures and services for public use; hospitals, schools, etc.	1.4 – 1.5

Source: Ontario 2001.

and properties. Some slopes may be unstable with factors of safety equal to, or greater than one because future soil conditions and dominant soil properties may differ from those used in estimating the initial factors of safety. A factor of safety determined by assuming a “worst-case” combination of factors influencing slope stability will have safety margins built into the analysis. The more common approach of analyzing for the most likely soil conditions and soil properties may require a higher factor of safety for an adequate margin of safety. A factor of safety should be conservative (significantly greater than 1.0).

An experienced geotechnical consultant will select a factor of safety to use in designing and constructing a stable slope. That selection takes into consideration such matters as: 1) uncertainties about present soil properties, present and future groundwater conditions, 2) the nature and consequences of slope failure, and 3) the level of risk that the property owner is willing to take.

An example of Ontario’s recommended design minimum factors of safety is shown in the following table.

Methods for estimating the probabilities of failure in slopes are becoming more commonly used. These methods take into account uncertainties about present soil properties that could not be thoroughly sampled and uncertainties about future groundwater conditions behind slopes. A geotechnical consultant experienced with these methods will show a client the percent probability of slope failure

occurring over a desired time span with no action to stabilize the slope and with selected stabilization designs.

The instability of a coastal slope at a site can be indicated by comparing the actual slope to the stable slope ratio (or ultimate stable slope angle) for the particular soils of a slope at that site that is not likely to fail under all expected future soil conditions, with a stated factor of safety. The stable slope ratio is a description of a slope. The ratio is expressed as unit vertical distance: horizontal distance of the slope. When slopes are re-graded, they should be re-graded to stable slope ratios. An example is given in the sidebar labeled “the importance of groundwater management” (on page 9).

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