Geotechnical Design and Factors of Safety

Technical Bulletin

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The Lakes and Rivers Improvement Act (LRIA) provides the Minister of Natural Resources with the legislative authority to govern the design, construction, operation, maintenance and safety of dams in Ontario. The Lakes and Rivers Improvement Act Administrative Guide and supporting technical bulletins have been prepared to provide direction to Ministry of Natural Resources staff responsible for application review and approval and guidance to applicants who are seeking approval under Section 14, 16 and 17.2 of the LRIA. All technical bulletins in this series must be read in conjunction with the overarching Lakes and Rivers Improvement Act Administrative Guide (2011).

Geotechnical Design and Factors of Safety

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1.0 General

This technical bulletin has been prepared to provide direction to Ministry of Natural Resources staff and guidance to dam owners in meeting requirements for geotechnical design and factors of safety when considering applications for approval under Section 14, 16, and 17.2 of the Lakes and Rivers Improvement Act (LRIA) for earthen embankment type structures, structures on overburden foundations, tailings dams and rockfill dams.

The standards and criteria outlined within this technical bulletin are intended to apply to dams (including the control structure and all appurtenant facilities) that hold back water in a river, lake, pond or stream to raise the water level, create a reservoir to control flooding or divert the flow of water; and are not intended to apply to other works subject to LRIA approval such as water crossings, channelizations, enclosures, pipelines and cables.

This technical bulletin must be read in conjunction with the Lakes and Rivers Improvement Act Administrative Guide (2011) and the Ministry of Natural Resource's Classification and Inflow Design Flood Criteria Technical Bulletin.

2.0 Geotechnical Aspects

Geotechnical design considerations should be assessed for the dam system that includes the dam (embankment, concrete and other) and appurtenant facilities, as well as their foundations, abutments and the reservoir.

The nature and variability of potential dam and foundation conditions should be defined by site investigations. These investigations commonly consist of test pitting, borehole drilling and sampling, in-situ testing, laboratory testing and groundwater monitoring to identify the geological and hydrogeotechnical conditions and to define engineering properties of materials used to establish appropriate design parameters. Site investigations should also pay particular attention to the identification of discontinuities and anomalies such as jointing, fissures and weak seams that, if present, will generally control foundation behaviour.

Engineering analyses should be performed to demonstrate that the dam, foundation and abutments will remain stable under all hazards and loading conditions. Geotechnical hazards for earth dams may include: seepage (internal erosion, piping and hydraulic fracturing), deformation (consolidation, slope instability, static and dynamic liquefaction) and surface erosion. Loading conditions include: end of construction, steady state conditions (operations), rapid drawdown, reservoir surcharge, wind and wave action and earthquake. Where significant changes in reservoir operations occur on a routine basis (peaking and storage operations) the impact of these operations (such as rapid drawdown) should be assessed and included in the analysis as normal operation loading conditions.

3.0 Embankment Dams

Analyses should be performed or design checks made to demonstrate that the dam, foundation and abutments will remain stable under all applicable design hazards and loading conditions. For existing Low and Moderate Hazard Potential Classification (HPC) dams that show no signs of distress and that have a history of good performance based on inspection by a Professional Engineer, and loading conditions are not anticipated to change, detailed analyses may not be required. The decision to perform detailed analyses should also consider whether life safety hazards to transient persons downstream of the dam can be shown to be minimal.

Overtopping as a result of flooding exceeding the reservoir capacity is the most common mode of failure for embankment dams. Although this is generally considered to be a hydrotechnical storage/discharge capacity issue, settlement of the dam crest can be one of the contributing factors and freeboard of embankment dams should be considered during assessment. Settlement may occur due to consolidation of the dam or foundation materials under static loading or may be induced by seismic activity, such as liquefaction. Some of the practices within industry to address settlement include foundation improvements, proper compaction of dam materials and cambering of dam structures. The impacts of dam and foundation settlement should be reviewed during the assessment of existing or new dams.

The susceptibility of the dam to piping development and a review of controls to mitigate piping should be considered in the design and assessment of embankments dams.

Seepage induced piping is the second most common cause of embankment dam failure. Piping occurs as a result of concentrated seepage from hydraulic gradients that can lead to fine particle migration and loss of materials, eventually resulting in formation of a “pipe”. Particle migration typically occurs when seepage passes from a fine-grained material into a coarser grained material or when material is carried into or through cracks or discontinuities in the dam, foundation or abutment materials. Cracking in embankment dams may occur as a result of differential settlement and hydraulic fracturing. Hydraulic fracturing occurs when internal hydraulic pressures exceed stresses within the embankment material. Typical controls for seepage-related issues with embankment dams include granular filter transition materials conforming to accepted filter criteria strategically placed within critical transition zones in the embankment and between the embankment and the foundation including foundation grouting, impermeable cut-offs, and upstream clay and low permeability blanketing.

Foundation “smoothing” to avoid differential settlement and stress changes and the use of appropriately flexible core materials are some of the common industry practices to reduce the potential for deformation induced cracking and the potential for the development of piping failure development.

The stability of the upstream and downstream slopes of the embankment and the potential for instabilities through the dam foundation needs to be assessed in establishing the integrity of embankment dams. The methods of analysis used may depend upon the characteristics of the dam and foundation, the material properties and the type and severity of the loads that the dam may be subjected to. In general, stability analyses can be performed using the limit equilibrium method of stability analysis.

Acceptance criteria are usually described in terms of factor of safety defined as the ratio of available shear resistance along a potential plane of failure compared to the activating shear forces along the same plane. The acceptance criteria for stability analyses are aimed at preventing deep-seated failures that could lead to a reduction in crest height or expose critical dam components and lead to dam breach.

Analysis of unusual or extreme loading conditions such as is associated with rapid draw-down or seismic loading may indicate the potential for shallow surface failures to develop, however, if these shallow failures do not lead to a reduction in crest height or expose critical dam components they may be considered to be acceptable based on engineering judgement. Where shallow failures are observed on an existing dam, this too may be acceptable provided that the dam owner has an acceptable inspection and maintenance program to identify and repair any such failure before they propagate into and possibly expose critical components of the dam structure.

3.1 Loading Combinations for Embankment Dam Stability Assessment

The stability of embankment dams shall be assessed under the following loading combinations:

1. End of Construction includes the following loads acting in combination: Dead Load; pore pressures and Uplift;
2. Long-term steady state seepage includes the following loads acting in combination: Dead Load; Hydrostatic Load (normal maximum operating level); Steady State Phreatic Conditions through the body of the dam, long term steady state pore pressures and Uplift;
3. IDF (Inflow Design Flood) Loading Condition includes the following loads acting in combination: Dead Load; Hydrostatic Load (IDF level); Steady State Phreatic Conditions in the body of the dam, long term steady state pore pressures and Uplift;
4. Earthquake loading includes the following loads acting in combination; Dead Load; Maximum Design Earthquake (MDE), Hydrostatic Load (maximum normal operating level); Steady State Phreatic Conditions in the body of the dam, long term steady state pore pressures and Uplift; and
5. Full or partial drawdown includes the following loads acting in combination: Dead Load; Hydrostatic Load (maximum normal operating level); Steady State Phreatic Conditions in the body of the dam with the upstream level suddenly dropped, long term steady state pore pressures and Uplift.

3.2 Embankment Dam Stability - Levels of Safety

The industry accepted factors of safety in Table 1 take into account the reliability of inputs to the stability analysis, the probability of the loading condition, and the losses of the potential failure.

Table 1 - Factors of Safety for Embankment Dam Slope Stability – Static Assessment and Seismic Assessment

Loading Conditions	Minimum Factor of Safety [Note 1]	Slope
End of construction before reservoir filling	1.3	Upstream and Downstream
Long-term (steady state seepage, normal reservoir level)	1.5	Upstream and Downstream
IDF loading condition	1.3	Upstream and Downstream
Full or partial rapid drawdown	1.2 to 1.3 [Note 2]	Upstream
Pseudo-static	Greater than 1.0	
Post earthquake	1.1	

Notes:
1. Factor of safety is the factor required to reduce operational shear strength parameters in order to bring a potential sliding mass into a state of limiting equilibrium, using generally accepted methods of analysis.
2. The higher factor of safety may be required if drawdown occurs relatively frequently during normal operations.
3. For flood conditions, the flood discharge capacity available and the calculated inflow design level shall be based on a reasonable assessment of dam operations considering the operating plan and shall take into consideration factors such as: accessibility during high flows; the potential for failure of electrical and mechanical systems; and inspection and maintenance programs.

For High or Very High HPC dams it may be appropriate to apply more sophisticated methods of analysis in addition to pseudo-static approaches. In these cases, other accepted criteria based on the state of stress and strain, and displacements, should be set for elastic response under usual loads, quasi-inelastic under unusual loads, and inelastic response under extreme loads. The stress-strain field, state of deformation, and distribution of pore water pressures in the entire continuum of the dam system should be evaluated for different loading cases and time stages. For example, during construction and immediately after construction; during impoundment and transient seepage; after full reservoir level has been reached and steady-state seepage has been developed; long term consolidation and creep; and transient loading conditions such as rapid or sudden reservoir drawdown, floods and earthquakes.

Acceptance criteria with respect to allowable maximum levels of stress, strain and displacement conditions are dependent on material properties including resistance. Where appropriate, these criteria must be established for each project on a case-by-case basis. It is possible, for example, to set criteria based on the maximum elemental or local factor of safety (i.e. ratio of maximum shear stress, failure or yielding strength). For slope stability concerns, such criteria could be established in order to provide a safety margin that is equivalent to the factors of safety shown in Table 1.

3.3 Additional Considerations for Embankment Dams

Additional considerations that should be taken into account during embankment dam design or assessment include:

1. Properly graded filters should be placed internally within the embankment and between the embankment, abutments and foundation, if migration of particles by seepage forces would otherwise be possible as the preferred method to control internal erosion;
2. The impact of any seepage along the axis of or leakage from conduits passing through the dam should be assessed, as necessary. Consideration shall be given to filter zones and cut-off measures;
3. Seepage exit gradients should be within acceptable limits for the embankment and foundation materials. The usual techniques used to reduce seepage through the pervious units are impermeable upstream blankets, cut-off trenches, grout curtains, sheet pile walls, slurry trench cut-off walls and other thin cut-offs. Where such measures are not possible, filter materials can be used to provide an acceptable exit condition;
4. The upstream slopes of the dam and its abutments should have adequate protection against erosion and possible breaching due to wave and ice action. Riprap or other erosion protection should be based on site-specific criteria based on expected water level, wind and wave action. The downstream slopes should be protected where necessary against the erosive action of runoff, seepage flows, traffic, frost and burrowing animals. Materials used for erosion protection should be hard and durable and not susceptible to breakdown;
5. Trees and woody shrubs should not be planted on any part of the dam embankment. Natural growth of trees and woody shrubs should be removed periodically; and
6. The dam should be protected from burrowing animals where necessary.

The following failure mechanisms should be assessed for seismic loading:

1. Embankment slope instability leading to overtopping;
2. Permanent deformation leading to overtopping;
3. Fissuration/ cracking leading to internal erosion failures;
4. Liquefaction (both triggering and post-liquefaction stability conditions);
5. Overtopping due to seismically induced landslides into the reservoir; and
6. Obstructions induced by landslides into the downstream channel preventing the safe discharge of flows.

4.0 Dam Foundations

Dams may be founded on rock, overburden of a combination of the two. Dam foundation treatment requires experienced engineering judgment. Specific issues to consider vary depending on the nature of the foundation.

4.1 Rock Foundations

In general, competent rock foundations will provide adequate bearing capacity for both embankment dams and concrete dams. However, the designer needs to consider the implications associated with soft rock foundations such as mudstones and siltstones with respect to both bearing capacity (in the case of concrete dams) and the potential for internal erosion along open discontinuities (in the case of concrete dams and embankment dams). A number of available laboratory tests exist to evaluate this potential when it is deemed to be a possible issue.

In particular, placement of fine grained materials overtop of bedrock foundations requires specific foundation preparation procedures to minimize the possibility of migration of the fine grained materials through the discontinuities in the rock mass. In-situ permeability testing and geological mapping can be used to assess the potential for this problem to occur. Foundation preparation measures often include washing and hand cleaning to expose adverse features such as vertical or near vertical bedrock ridges that could result in high stresses or differential settlements. Treatment of the features using such techniques as dental concrete, slush grouting, curtain grouting and base concreting are commonly used. Particular attention should be paid to in-filled discontinuities or weathered discontinuities that may progressively open under the effects of the post impoundment hydraulic gradient.

Limestone can, in some instances, create special problems associated with karsticity. Karsticity occurs as a result of a progressive dissolutioning of carbonate rocks exposed to water and carbon dioxide. In the presence of dissolved carbon dioxide, maximum solubility increases dramatically. Therefore, a karstic formation implies the presence of a network of solutioned, often highly permeable, discontinuities which are, by definition, connected to the surface so that the free carbon dioxide necessary to allow the solutioning process to continue is available. This fact means that karst foundations are usually associated with highly deformed, complex, rock masses that have pervious windows extending directly to the foundation surface. Treatment of such foundations often requires an extensive grouting programme to reduce post impoundment seepage to manageable levels. In many karst foundations, highly soluble gypsum and anhydrite can be present along discontinuities or as interbeds within the rock mass. Treatment of such features is generally very difficult and it would be typical to provide provisions in the design to allow for future remedial foundation grouting as these features dissolve.

4.2 Overburden Foundations

For dams constructed on overburden foundations it is necessary to consider the bearing capacity of the foundation materials and the possibility of long term settlement that could affect freeboard or cause cracking of the impervious core. Special care is necessary when embankment dams are situated on a variable foundation consisting of different overburden types or partially on overburden and partially on bedrock. For these situations, special care is required in the design of the dam to account for the possibility of differential settlement at the boundaries between the different material types that could lead to cracking or hydraulic fracturing. Measures might include flattening the dam section to reduce the stresses at the foundation level, provision of a wider core or filters, design of the core materials to provide an enhanced degree of flexibility or the use of alternative materials, etc.

Stability analyses of embankment dams constructed on an overburden foundation must consider the potential for failure through the dam fills and through the overburden foundation itself. Depending on the nature of the foundation analyses may need to consider the potential for liquefaction, the potential for a sudden loss of strength due to collapse of the soil structure, as can occur in Champlain Sea clays in and around the Ottawa area and the permeability of the soil.

Treatment of permeable overburden foundations beneath embankment dams may require the use of a core trench or, for deeper foundations, the use of specialized grouting techniques, the installation of an impervious cut-off wall (cement-bentonite, plastic concrete, sheet pile, timber, geosynthetic or other depending on the nature of the foundation and the hydraulic head) or the provision of an upstream impervious blanket specifically designed to reduce seepage levels and hydraulic gradients to acceptable levels. In the assessment of seepage control measures, designs should ensure that the post construction hydraulic gradient at all unfiltered exits is such that the potential for internal erosion (piping) is minimized.

Permafrost foundation subsidence occurs as reservoir impoundment raises the mean annual ground temperature, which can cause an unusual degree of movement on a dam. Foundations in intermittent permafrost zones are particularly susceptible to mean ground temperature changes and can result in higher differential settlements throughout the structure. Dams constructed on permafrost affected foundations must be capable of deforming in response to potentially large differential settlements which are experienced as a result of thawing of variable ice content in permafrost foundations. For new dams, foundation exploration and treatment must be sufficient to limit thaw settlement and pore pressures to acceptable amounts. Special attention to the foundation may be required where ice lensing in the shallow foundation soils could potentially establish piping failure through those soils under thawing conditions.

If foundation settlement has steepened embankment slopes above the original design, slope stability analysis should be performed. Likewise, the effect of observed cracking and/or redistributed pore water pressures on stability should be analyzed. A distinction should be made between the stability of frozen and thawed dams.

The settled crest of the dam should be verified to have sufficient freeboard based on conventional wind and wave analysis plus an additional safety margin equal to the expected ultimate settlement of the dam crest. Crest surveys and settlement pin monitoring provide an ongoing record of settlement.

Current design practice requires dams on permafrost to be constructed of self-healing granular materials. Embankment zones are typically designed to permit anticipated future upgrading while preserving continuity of fill zones.

4.3 Reservoir Rim

The stability of reservoir slopes and discharge channels should be evaluated under seismic loads, heavy rainfall, rapid drawdown, operational regimes, and any other loading conditions, if slope failure could induce waves that pose an unacceptable risk to public safety, the dam or its appurtenant facilities.

4.4 Timber Crib Dams

A timber crib dam relies on the integrity of the timber frame and the materials used to fill the crib for stability. Therefore, in assessing the suitability of an existing timber crib dam, signs of deterioration of the crib and loss of materials within the crib need to be evaluated. Assessment of the stability of a timber crib dam requires an evaluation of the sliding stability of the structure at the foundation contact, and an evaluation of the potential for circular failure though the overburden foundation. In addition, the potential for overturning requires evaluation. Table 2 presents the minimum factors of safety for timber crib dams.

Table 2 - Factors of Safety for Timber Crib Dams

Loading condition	Minimum Factor of Safety
Usual – Sliding	1.5
Usual – Overturning	2.0
Unusual – Sliding	1.3
Unusual – Overturning	1.5

Other considerations for timber crib dams include; toe stress, foundation erosion (i.e. piping), timber material condition, sheathing, and cut-off walls.

5.0 Tailings Dams

Tailings are the waste material transported by water and generated from the mining and processing cycle of metal recovery from naturally occurring economic ore deposits. Tailings dams are embankment dams with the unique characterization which can be constructed from tailings waste material.

Tailings dams share with conventional embankment dams, all design and safety evaluation principles but have a number of unique considerations that must be recognized and addressed during the design and construction phases of the dam life cycle.

Tailings dams, for example, can be constructed from tailings materials and are generally constructed in phases, often over a long period of time. In addition, tailings dams must also be maintained for an indefinite period, following completion of the associated mining activities. Some of the unique characteristics associated with tailings dams include the management of contaminated water management in tailings ponds, specific dam design criteria such as the width of the tailings beach, location of reclaim pond, method of construction (e.g. upstream, downstream, centreline), maintenance of drainage systems, material used for construction i.e., tailings; and the practicalities associated with the operation of the dam, including periodic raising of tailings dams and the ongoing rise of the impounded solids and fluids during the mine production phase.

Permafrost can cause special problems in tailings facilities as the condition of the frozen ground can change. Further, the depositional pattern of tailings in the reservoir/basin should be monitored because of the extremely low temperatures in permafrost areas. Long term changes in the permafrost and active zone should be considered, particularly for periods of temporary suspension of mining activities, or closure.

Given these considerations, the standards for tailings dams may be substantially different from those applicable to conventional embankment structures and careful consideration of these issues forms part of the design of any tailings dam.

6.0 Flow Through Rockfill Dams

'Flow-through' rockfill dams are designed to withstand the combined effects of the action of (i) the flow-through seepage emerging from and accumulating on the downstream face, and (ii) any overflow. The latter is that part of the Inflow Design Flood (IDF) which cannot pass through the rockfill. The dam is designed to withstand the combined effects of these seepage forces without the migration of rock particles, whether singly or en-masse.

Flow through rockfill dams, or 'leaky' dams, are designed to prevent flow over the crest, unless the downstream slope and abutments are specifically designed to limit erosion. Erosion protection from overtopping can consist of armour stone or may make use of artificial means to limit erosion involving the use of metal or wire. In such cases, the effects of the corrosion of the metal or wire on the life-span of such reinforcement must be considered. Allowance must also be made for the possible accumulation, over time, of debris on the upstream face of the dam. If this debris is not removed, it will reduce the quantity of flow that can pass through the embankment and correspondingly increase the flow within the impoundment and potentially over it. Frazil ice can have the same effect.

Glossary of Terms

Appurtenant Facilities: Means structures and equipment on a dam site including, but not limited to, intake and outlet structures, powerhouse structures, tunnels, canals, penstocks, surge tanks and towers, gate hoist mechanisms and their supporting structures, spillways, mechanical and electrical equipment, water control and release facilities.

Cut-off Wall: A wall intended to prevent seepage or undermining**.**

Cut-off Trench: A trench filled with impervious soil, such as clay, to prevent seepage of water under a dam.

Dam: For the purpose of this technical bulletin, a dam is defined as a structure that is constructed which holds back water in a river, lake, pond, or stream to raise the water level, create a reservoir to control flooding or divert the flow of water.

Dam Owner: the owner of a dam, structure or work and includes the person constructing, maintaining, or operating the dam, structure or work; ("propriétaire").

Embankment: A bank of earth or rock constructed above the normal (natural) ground surface.

Filter: A granular material placed to facilitate drainage and at the same time strain or prevent the admission of fine soils. A filter may also be constructed of a cloth-type material (geotextile).

Foundation: The soil or rock upon which the structure or embankment rests. An alternative definition is similar to footing.

Frazil Ice: Also known as slush ice is formed by agitated water in rapids during cold spells. Frazil develops when water is super cooled (cooled below freezing) but solid ice is prevented by fast flowing agitated water; instead ice crystals form to create an ice crystal blizzard. When the ice crystals reach calmer water, they rapidly bind together to form large ice masses.

Groundwater: Sub-surface water or water stored in the pores, cracks, and crevices in the ground below the water table.

Grout Curtains: A row of holes drilled into rock beneath a dam filled with cement or chemical grout to seal the fissures in the rock.

Inflow Design Flood: The maximum flood entering a reservoir for which the dam and reservoir are designed.

Piping: The movement through a dam of water and soil. Uncontrolled piping can lead to serious internal erosion and failure.

Riprap: Rough stone of various sizes placed compactly or irregularly to prevent scour by water or debris.

Tailings Dam: A dam constructed to impound an area for the capture of mine waste and process water. These dams may be constructed of mine waste material.

Tailwater: The downstream water (sometimes the downstream water depth).

List of Acronyms

HPC	Hazard Potential Classification
IDF	Inflow Design Flood
LRIA	Lakes and Rivers Improvement Act
MDE	Maximum Design Earthquake
MNR	Ministry of Natural Resources