# IMPACTS OF GLACIALLY-MODIFIED VALLEY LAND SYSTEMS ON THE GEOTECHNICAL DESIGN, CONSTRUCTION AND PERFORMANCE OF DAM FOUNDATIONS IN CANADA

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## ABSTRACT

*Dams are frequently constructed in glaciated valleys that were formed or modified in the Quaternary Period by subglacial erosion, glaciofluvial meltwaters and/or para-glacial processes. These are com-plex landforms that can exhibit a range of geometries, geomorphological characteristics and glaci-genic sediment infill. Geohazards include irregular bedrock profiles, artesian pressures, discontinuous lenses of weak ground or glaciotectonically modified bedrock. Seepage within a dam's foundation can significantly influence its design, construction and performance of dams constructed across these types of valleys. This often requires the installation of cut-off walls, grout curtains, drainage systems or upstream blankets. The depths of glacial valleys can be greater than 100 m, resulting in construc-tability issues for cut off walls and grouting.*

*Glacial valley architecture and geometry is influenced by a range of spatial and temporal factors such as rock mass controls and climate conditions. The classic U-shaped valleys are formed by prolonged and episodic glacial advances and retreats and infilled with subglacial traction tills, glaciolacustrine and glacial fluvial deposits that reflect spatial and temporally changing depostional environments. Buried valleys are channels that often have no surface morphological expression but can be laterally and vertically extensive, and can present a geohazard for dams, if they are not sufficiently character-ized.*

*The aim of this paper to provide the dam engineering and safety industry with an overview on glaci-ated valley landsystems; how these are formed; associated geohazards; and the significance to dam construction. Case studies from Canada are presented in this paper.*

## 1. INTRODUCTION

Approximately 30% of the Earths land surface was glaciated during the Last Glacial Maximum (LGM), which occurred 22-20,000 years ago. In comparison, modern-day glaciers currently cover approximately 10 % of the Earth's land surface (Martin et al, 2019). The landscape of Canada in particular was extensively impacted by the Pleistocene glaciations. At the time of the LGM, the entire land surface of Canada was covered by the Cordillerian and Laurentian Ice-sheets (Dyke, 2004). This produced a post-glacial landscape, in which the engineering geological characteristics and geotechnical properties of sediments, landforms and bedrock, are predominantly controlled by glacigenic processes.

Given the extent of the Quaternary glaciations, it is no surprise that hundreds of large dams have been constructed across Canada within valleys that were formed or modified by glacigenic processes and have been constructed using glacigenic earthfill. The valleys that form the foundation and abut-ment of the dams are complex landforms that can exhibit a range of geometries, geomorphological characteristics and glacigenic sediment infill. These valleys can contain foundation defects that may present a significant geohazard to dam construction, reservoir impoundment and ongoing operations, if they are not identified and appropriately considered by designers and owners.

It is apparent from a literature review of available dam designs, construction projects, operations, and dam safety incidents that there is a surfeit of individual case studies. With the notable exception of Lajeunesse (2014), the author is not aware of any attempt to synthesis these into a larger study. The aim of this paper to provide the dam engineering and safety industry with an overview on glaci-ated valley landsystems; how these are formed; associated geohazards; and the significance to dam construction. Case studies from Canada are presented in this paper.

## 2. GLACIAL VALLEY LANDSYSTEMS

A landsystem is defined a large area (100 km2) with a recurring pattern of landforms, soils, vege-tation, geology and hydrological regimes (Lawrence, 1993). Glacial landsystems encompass:

(1) *Ice-sheets and caps*. These are large masses that submerge the landscape and are largely inde-pendent of bed topography. These were present during the Laurentian glaciations and are now, observed in Greenland and the Antarctic. Dams constructed in valleys in the Prairie, Central and Atlantic regions of Canada are predominantly associated with this type of landsystem.

(2) *Glaciers constrained by topography*. These include icefields that are influenced by the under-lying topography, such as the Columbia and Patagonia Icefields; single-branch and dendritic valley glaciers; transection glaciers, cirque glaciers and piedmont glaciers (Benn and Evans, 2010). Dams constructed in parts of British Columbia, Alberta, Yukon and Northwest Territo-ries are predominantly associated with this type of landsystem.

The cross-sectional shape is classically described as U-shaped, in comparison to the V-shaped val-leys formed by fluvial processes in non-glaciated settings. Coles (2014) provided a useful discussion on the evolution of this concept through works in the early 19th century, Svensson's (1958) parabolic curve, Harbour (1992) work on the development of U-shaped valleys and Philips (2009) use of geo-graphical information systems (GIS) to analyze landscape geomorphology from digital elevation models (DEM). It is important to recognize that the above concepts are concerned with the surface morphology of the valley cross-section.

This paper has adopted the descriptive terminology for glacial land systems based on Giles et al (2017), Benn and Evans, (2010), and Bennet and Glasser (2009). Table 1 provides a summary of the land system, topographical description, formation and its engineering significance.

**Table 1** : Summary of Glacial Valley Land Systems (descriptions adapted from Giles et al, 2017, Benn and Evans, 2010; Bennet and Glasser, 2009) utilized for dam locations

| **Valley land system** | **Topographical Description** | **Formation** | **Engineering significance for dam foundations** |
|---|---|---|---|
| Valleys formed from areal scour | Areas of low-relief smoothed into streamlined rock knobs and basins with whale-backs and roche mou-tonees morphology. Bedrock sur-face may contain striations, gouges and fractures.<br>Mega-scale glacial lineations, flutes and quarried rock basins will be pre-sent depending on effective normal pressures, cavity and ice contact condition.<br>Localized glacigenic deposition in low-points | Large-scale ice sheet erosion of bedrock in lowland areas. Con-trolled by pre-glacial weathering characteris-tics and bedrock jointing pattern. | Disturbed and sheared bedrock; irregular bedrock profile, voids, weak / compressible soils |
| Terrestrial glaciated valleys and troughs | Relatively straight, steep-sided, U-shaped valley with a parabola cross-profile and irregular long profile with rock riegel and over-deepened rock basins.<br>Associated with hanging valleys, trough heads, criques, cols, horns, nuantaks, roche moutonees, crag and tails, glacial erratics | Eroded channels of pre-sent or former glaciers or ice streams | Irregular bedrock profile with over-steepened zones, disturbed and sheared bedrock, anisotropic permeability, anisotropic strength, weak / compressible soils |
| Hanging valleys | Tributary valley with a floor that is significantly above that of the adja-cent main valley. | Glacial widening and/or deepening of the main valley | Disturbed and sheared bedrock, over-steepened zones |
| Rock basins | Over-deepened lake or sea filled bedrock depression | Calved out by glacier moving downstream | Disturbed and sheared bedrock, voids, anisotropic strength, compressible soils |

| | | | |
|---|---|---|---|
| Cirques | Large bedrock hollows that open downslope and are bounded upslope by a cliff, steep slope, or arcuate headwall. | Glacial erosion on mountainside, periglacial freeze-thaw weathering and glacial quarrying | Disturbed and sheared bedrock, over-steepened zones, |
| Tunnel Valleys and Channels | Large, sinuous and steep-sided val-leys. Eroded incisions into glaci-genic units and/or bedrock. Orien-tated sub-parallel to the longitudinal ice flow. Wide-range of morpholo-gies: straight, sinuous, dendritic and anatomizing. Infilled with sediment and water-bearing. | Subglacial meltwater erosion beneath ice sheets, through rapid drainage of stored water or meltwater derived drainage | Groundwater, anisotropic permeability, weak / compressible soils, Voids |
| Lateral Meltwater Channels | Channels of varying profile formed in groups or single channels orien-tated sub-parallel to the land topog-raphy. | Eroded by meltwater along or adjacent to ice margins | Groundwater; anisotropic permeability, weak / compressible soils; voids |
| Ice-marginal Channels | Channels of varying profile formed in groups or single channels orien-tated parallel to the ice-front due to the land topography. Glacial fluvial and postglacial deposits present in the channels. Can start and end ab-ruptly. | Release of large volumes of supraglacial or sub-glacial meltwater. Downcut into bedrock and glacigenic deposits by proglacial meltwater | Groundwater; anisotropic permeability, weak / compressible soils; voids |
| Subglacial Gorges | Narrow and deep channels incised into bedrock with irregular cross-sections. Often straight and have inconsistent gradient to bedrock structure | Subglacial meltwaters exploiting preexisting structural weakness in the bedrock | Irregular bedrock profile with over-steepened zones, anisotropic permeability |
| Fjords | Deep valleys with smooth Flooded, long, narrow coastal inlets with steep sides or cliffs. Often overlooked by hanging valleys | Postglacial flooding of glaciated valley in coastal setting | Over-steepened zones; over-stressed zones, disturbed and sheared bedrock; anisotropic permeability; aniso-tropic strength |

## 3. GEOHAZARDS ASSOCIATED WITH FOUNDATION DEFECTS IN GLACIATED VALLEYS

Glaciated valleys are geohazards and require extensive investigation to appropriately characterize and understand foundation defects. External hazards can include:

- Irregular bedrock profile and over-steepend zones. Glacial erosion by quarrying and abrasion can result in steep, sub-vertical rock faces. Voids, potholes, overhangs, and weak seams are likely to be present. Borehole coverage can be inadequate and miss deeper zones or gorges within the larger channels. Examples include the Manic Dam (Dascal, 1979), Peribonka Dam (Balian et al, 2007) and Revelstoke Dam (Imrie and Moore, 1993)
- Disturbed and sheared bedrock. The quarrying, freeze/thaw and periglacial action can shatter the bedrock and jack-open discontinuities. In regions, where clay-shales are predominant (Al-berta and Saskatchewan), the advance of glaciers and subsequent valley rebound after retreat can shear the bedrock, introduce slickensides into the fabric and mobilize residual strengths. Examples include the Site C Hydroelectric Dam (Hiedstra et al, 2016)
- Seepage and anisotropic permeability. Glaciated valleys frequently contain massive deposits of glaciofluvial sands and gravels. These can increase the potential for reservoir leakage, internal erosion in the foundation and uplift. Seepage within a dam's foundation can signifi-cantly influence its design, construction and performance of dams constructed across these types of valleys. This often requires the installation of cut-off walls, grout curtains, drainage systems or upstream blankets. The depths of glacial valleys can be greater than 100 m, re-sulting in constructability issues for cut off walls and grouting.

- Weak layers in the foundation. Glaciated valleys can contain glaciolacustrine units presenta-tive of proglacial lakes. Examples include the Mt Polley tailings storage facility, which failed in 2014 (Morgenstern et al, 2015), Lake McGregor Dam (Peters and Lamb, 1979)

## 4. CASE STUDY 1: DAMS CONSTRUCTED IN AREAS OF AREAL GLACIAL SCOUR - QUEBEC

This is a regional-scale landscape that is formed from sub-glacially eroded bedrock, which manifests itself as rock knobs, over-deepened rock basin, glacial lineations and megaflutes. The advance of the wet-based glacier abrades and quarries the bedrock. Basins of valleys may reflect zones of less re-sistant rock, or increased discontinuity density. Deeper, river valleys may form the coalescence of tributary basins. Valley infill will typically comprise localized glacial tills, glaciofluvial, lacustrine, post-glacial fluvial deposits, and peat / muskeg. Relief will be typically less than 100 m (Benn and Evans, 2010). This type of land-system is encountered through the Canadian Shield in Northern Que-bec, Ontario, Labrador and Nunavut.

Dams constructed in these landscapes are dependent on the hydrological basin characteristics de-rived from the areal scouring. Given the low relief and 'knock and lochan' topography, the dam sys-tems often comprise a large dam constructed across the main river valley with saddle dams con-structed across smaller depressions to form the reservoir. Examples of dam construction are encountered in Quebec, Manitoba, Ontario and Labrador in Canada.

The La Grande Riviere Project in James Bay, Quebec is a famous example of dam construction in this type of landscape. This mega-project comprised the construction of 11 generation stations be-tween 1971 and 1996 with a total capacity of 15,300 MW. The dams and dykes for the La Grande 1 to 4 were constructed on areal-scoured metamorphic and igneous bedrock of Precambrian age. The Labrador glaciation had originated in north central Quebec with westward ice sheet advance towards James Bay and Hudson Bay. Construction of the dams, dykes and spillways required extensive cut off walls, grouting, and foundation preparation in the glaciotectonically disturbed bedrock. Glacio-marine clays and silts were encountered towards the Hudson Bay, requiring ground improvement (Société d'energie de la Baie James, 1988).

## 5. CASE STUDY 2: DAMS CONSTRUCTED IN ALPINE GLACIATED VALLEYS – KOOTENAY REGION, BRITISH COLUMBIA

The Kootenay region contains numerous abundant hydroelectric dams that were constructed from the 1890's onward in former glaciated valleys. The region is defined as a glaciated valley landsystem affected by the Cordillerian 'Fraser' Glaciations during the Late Pleistocene. Major ice streams would have advanced southwards from the Fraser Divide through the adjacent Columbia, Slocan and Koo-tenay Lake Valleys across the US border into Washington State and Idaho. The icesheet was formed by the gradual coalescence of valley and piedmont ice lobes. Deglaciation resulted in the development of a transient proglacial lakes throughout the area.

The Revelstoke Hydroelectric dam system was constructed between 1981 and 1984 across the Kootenay River Valley. It comprises a 175 m high concrete gravity dam in the river canyon with and a 125 m high earthfill dam on the right bank terrace. Adverse bedrock and glacigenic geology was not fully appreciated prior to construction and led to a number of major design impacts which had to be dealt with during the construction phase (Imrie and Moore, 1993). The concrete dam foundation was in a steep-sided post-glacial canyon cut into rock adjacent to a broad ancestral river valley, in-filled with glacigenic and post-glacial deposits. The earthfill dam adjoins the concrete dam and stretches across this infilled valley. The bedrock surface forming the base of the glaciated valley is cut by two steep-sided buried canyons encountered during construction (Imrie and Moore, 1993).

The investigations indicated that the valley was infilled with interbedded glacigenic and post-gla-cial deposits comprising sand, gravel and cobbles. Localized zones of soft silt and clays were encoun-tered. The advance of the ice-sheet had eroded meta-sediments of the Monashee Metamorphic Com-plex to form an undulating buried valley profile (Figure 1) with two buried channels present. The buried channels required extensive rock excavation to shape the core contact foundation to minimize differential settlement and cracking within the core. When exposed, the channels were found to be irregular with overhangs, scour holes, potholes and sub-vertical sidewalls (Figure 2b). A 76 m deep core trench supported with electroosmosis was excavated through the valley infill to bedrock (Taylor and Lou, 1983).

The Kootenay Valley between the west arm of the Kootenay Lake and its confluence with the Columbia River contains six hydroelectric dam systems: Brilliant Dam, Corra Linn, Lower Bonning-ton, Kootenay Canal, South Slocan and Upper Bonnington (Bayliss et al, 2019). The West Kootenay River Valley is a steep-sided valley that was modified by the Cordillerian 'Fraser' Glaciations in the Late Pleistocene. Major ice streams would have advanced southwards from the Fraser Divide through the adjacent Columbia, Slocan and Kootenay Lake Valleys and tributary glaciers would have filled in the West Kootenay River Valley and quarried and abrading the granitic bedrock. The retreat of the icesheet northwards resulted in the development of proglacial lakes and eventually the valley became a spillway for glacial outburst floods (jökulhlaup) into the Columbia River System (Peters, 2012).

**ABSTRACT:**

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**Fig. 1** : Profile of buried valley beneath the Revelstoke Dam (from Taylor and Lou, 1983)

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## INTRODUCTION

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**Fig. 2** : (a) Construction of the Revelstoke Dam (b) Excavation of buried channel beneath the earthfill dam

The jökulhlaups or the subsequent, paraglacial fluvial processes resulted in the downcutting of the river through pre-existing glacigenic materials within the Kootenay Valley floor until bedrock was encountered. The granodioritic bedrock forms the foundation of the concrete gravity dams.

The Duncan Dam was the first of the Columbia River Treaty dams to be built in 1967. It retains the Duncan River with a 45 km reservoir and does not generate any electricity. Its main purpose is to hold back water in relation to the U.S Army Corps of Engineers Dam at Libby, Montana to regulate water flows through the Kootenay River Dams.

The valley was modified by the Kootenay Glacial Lobe, which advanced southwards along the Purcell Trench into Montana, USA. Prior to construction, the valley was broadly U-shaped with a wide, glaciofluvial sandar (Figure 3). The bedrock profile of the buried valley was up 380 m deep with a narrow, steeply-incised gorge present beneath the center of the valley. This was infilled with a basal unit of dense sands and gravels overlain by a 90 m thick unit of 'lacustrine' deposits comprising silt and fine sand. The upper unit was alluvial sands and gravels up to 24 m thick. It possible that the gorge represents a preglacial fluvial gorge, similar to the gorges observed in Quebec (Lajeunesse, 2014). During construction, several transverse cracks developed due to differential settlement of 4.3 m thickness over 120 m recorded. This required a change in the design in the areas of the dam that experienced the most severe settlement with the core moved from the center of the dam to the up-stream face; pre-loading and flattening the slopes of the dam (Gordon and Duguid, 1970).

The Waneta Dam was constructed in 1951-53 on the Pend D'Oreille River near its confluence with the Columbia River. The concrete gravity dam is founded directly on glaciated bedrock; however, there is a buried channel is located approximately 0.8 km upstream of the dam. The channel connects the Pend D'Oreille River to the Columbia River and is 150 m wide, 90 m deep and infilled with alluvium, gravel and glacial till. The surface expression of the channel cannot be clearly determined from aerial imagery. A system of drains were designed by Dr K. Terzaghi during construction to intercept groundwater flow from the Waneta reservoir.

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**Fig. 3** : Site of the Duncan Dam prior to construction

## 6. CASE STUDY 3: DAMS CONSTRUCTED IN ALPINE GLACIATED VALLEYS – ROCKY MOUNTAINS, ALBERTA

This region is a glaciated valley landsystem located in the Front Ranges of the Rocky Mountains. This is a northwest-tapering zone of thin-skinned, thrusts and faults developed during the Cordillerian Orogeny. Post-orogenic differential erosion has resulted in high relief of the Southern Canadian Rock-ies and the eastern Foothills. The Front Ranges are formed from imbricated, dipping thrust sheets involving Paleozoic carbonates. The regional strike of the structures and bedrock is typically north-south and this has controlled the erosional pattern of advance and retreat of Cordillerian glaciers, whereby the geomorphology is expressed as linear valleys with intervening mountain ridges. Tribu-tary cirques, rock basins and hanging valleys are common.

Five hydroelectric dams were constructed by the Calgary Power Company (TransAlta) in this re-gion between the 1920's and 1950's. The Three Sisters and Cascade Dam systems were constructed in the Spray River Valley, which is a 30 km, NW-SE trending U-shaped glaciated valley. The Inter-lakes and Poccaterra Dams were constructed within a large rock basin that was formed by multiple northward advances of the Kananaksis Valley Glacier (Hawes, 1977). The Barrier Dam was con-structed further north at the mouth of the Kananaksis Valley was affected by multiple advances of the Kananaksis Valley Glacier and the adjacent Bow Valley Ice Lobe, which formed an ice-damned gla-cial lake at dam site.

A case study regarding the performance of the Three Sisters Hydroelectric Dam was presented by Wade, Courage and Keys (1986) and Houston and Morgenstern (1989). The 21 m high, Three Sisters Dam was constructed over 60 m of glacial tills, glaciofluvial deposits, and colluvium. No cut off wall was considered in the original design of the dam, when constructed in 1951. Seepage was observed after first filling. Sinkholes on the right abutment and in the intake channel for the buried penstock at the base of the dam fill, were first observed in 1974 when the reservoir was drawn down in preparation for downstream remedial work. Additional sinkholes, observed in subsequent years during low res-ervoir levels, varied in size from small depressions characterized by an accumulation of twigs depos-ited in a vortex to one measuring 5 m in diameter by 1.5 m deep. The remedial work consisted of installing a partial sheet pile cut-off near the upstream toe, placing an impervious blanket on the upstream slope of the dam and constructing a concrete transition basin with an underlying inverted filter blanket in the tailrace downstream of the powerhouse.

Further to the north, the Bighorn Dam was constructed across the North Saskatchewan River Val-ley, which was formed by the eastwards advance of Cordillerian ice-sheets into prairies. The dam comprises a 91 m high, zoned embankment dam constructed on 64 m of glacial fluvial sands and gravels. A slurry trench cut off wall was installed into the channel; however, upon first filling of the reservoir in 1972, erratic drops in piezometric heads in the alluvium upstream of the cut-off and sig-nificant downstream leakage prompted the construction of a weight berm at the downstream toe and implementation of a program of regular monitoring of all piezometers and seepage measuring facili-ties (Wade et al, 1988).

## 7. CASE STUDY 4: DAMS CONSTRUCTED OVER TUNNEL VALLEYS, ALBERTA

Tunnel valleys or channels are large, elongate, depressions with over-deepened area along their floors that are cut into bedrock or glacigenic sediment. They are encountered as sinuous or linear landforms or as anastomosing networks. The glacigenic infill is characteristically dominated by sediment gravity flow facies and thick units of glaciofluvial sands. Till are rare and, where present, occurs along valley sides (O Cofaigh, 1996). They may not have a clear topographical expression on the surface. These can be up to 100 km long and 4 km wide.

In Northern Alberta, Canada, the Jackpine Mine Tailings Dam was constructed over the Kearl Channel. This is a regional-scale, sinuous valley system with numerous tributaries that was formed beneath the Laurentian ice-sheet, when the ice margin was within the region. Atkinson et al (2013) hypothesized that the channels were formed by the periodic release of sediment-laden basal meltwater (jokulhlaups) beneath the ice sheets, using either pre-existing valley systems or incising new ones, followed by waning or periods of low meltwater discharge. The valley was infilled with glacial-fluvial sands and gravels with localized rafted bedrock and capped with glacial tills and rafted bedrock (Bay-liss et al, 2015). The presence of this unit required seepage control measures to control groundwater pressures in the channel beneath the tailings dam.

Further to the south, the South Tailings Pond was constructed over a similar channel called the Wood Creek Sand Channel. This required the installation of pressure relief wells to reduce artesian pore pressures in the aquifer. Groundwater modelling had predicted artesian pressures to be 20 m above existing ground elevation without mitigation (Stephens et al, 2011).

## 8. CASE STUDY 5: DAMS CONSTRUCTED IN GLACIATED VALLEYS, GORGES AND FJORDS, - EASTERN QUEBEC

The impacts of an irregular bedrock profile was encountered during construction of the 83 m high, Peribonka 380 MW hydroelectric dam in Quebec between 2004 and 2007 on a deep glacial valley that comprised a deep 126 m deep 'main' valley and secondary 30 m deep valley on the right bank (Figure 1). The walls of the main valley were formed by granite and andesite and was near-vertical with localized overhangs. Both valleys were infilled with alluvium. The seepage control beneath the dam comprised plastic concrete cut-off wall with 0.5 m embedment into rock (HydroQuebec / SNC Lavelin, 2004; Balian et al, 2007; 2010).

Lajeunesse (2014) studied the geomorphology, geometry and infill of buried gorges and valleys beneath several hydroelectric dams constructed by HydroQuebec near the Gulf of St Lawrence. His studies suggested that glaciers had modified pre-existing valleys with narrow, deep gorges forming a V-shaped valley within a larger U-shaped valley. Evidence of potholes, natural pillars, furrows, flutes and polished bedrock was observed during foundation preparation for Manic-2, Manic-3 and Manic-5, Outardes 3 and 4, and several other hydroelectric developments.

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