University of Southern Queensland
Faculty of Health, Engineering and Sciences

Optimising Earth Dam Design in Seasonal Freeze-Thaw Climates

A dissertation submitted by

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Abstract

This research project explores the challenges associated with the design and construction of earthen embankment dams in climates where seasonal temperature variations result in freeze-thaw cycling of the material in the structure and winter conditions inhibit construction. Engineers must take into account seasonally limited construction schedules and adapt their methods to ensure that the dam is built properly under freezing conditions. Standardised design methodology and construction techniques are not readily available to engineers in many of these regions resulting in a variety of adopted practices and design parameters.

The project aims to identify common issues and provide a series of recommendations that could potentially be used as a platform for a standardised set of guidelines for use by engineers involved in earth dam design in seasonally cold regions. A comprehensive literature review was paired with practical experience from engineers in the field to provide a broad and functional source of information. Key areas explored in the project are design principles, material selection and construction methods specifically in application to seasonally cold regions.

Some key findings that came out of the investigation included the detrimental effects of repeated cycles of freezing and thawing on fine grained soils, the high performance of alternative barriers such as asphalt and bituminous membrane and the specialised techniques developed to enable dams to be constructed during winter with little effect on quality.

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Limitations of Use

Certification

I certify that the ideas, designs and experimental work, results analyses and conclusions set out in this dissertation are entirely my own effort, except where otherwise indicated and acknowledged.

I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

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Signature

24/10/2013

Date

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Glossary of Terms

ASCE: American Society of Civil Engineers

CRREL: US Army Cold Regions Research and Engineering Laboratory

ICOLD: International Commission on Large Dams

USACE: US Army Corps of Engineers

Cold Climate Region: Generally defined as a location with a minimum seasonal frost penetration of 300 mm (Jantzer & Knutsson 2007).

Embankment dam: A dam built using either earth or rock-fill, can be homogenous or composite in configuration.

Earth dam: An embankment dam constructed using compacted earth as the predominant fill material. Also known as a rolled-earth dam or earth-fill dam.

Rock-fill dam: A type of embankment dam where the predominant fill material is rock or crushed stone. Rock-fill dams can also be built as zoned dams with impermeable clay or till cores.

Freeze-thaw climate: Also referred to as seasonally cold climate. A climate where temperatures are cold enough during winter for significant ground freezing to occur, and warm enough during summer for significant ground thaw.

Freeze-thaw cycle: Periodic cycle of freezing/thawing of the ground generally due to seasonal temperature fluctuations.

Fine grained soils: Any soil composed of fine particles, principally clays, usually high plasticity.

Till or glacial till: Soil type commonly found in cold regions due to glacial depositions. Generally characterised by its range of grain sizes from fine clay all the way up to boulders and commonly used as an impermeable core for earth dams due to its performance and availability.

Ice lens: Ice crystals formed within the soil due to frost penetration in the presence of water or snow and ice being mixed with fill material during winter construction.

Ice front: The leading edge of an icy section of soil. The control of ice fronts is a key factor in managing seepage in large earth structures in cold regions.

Geotextile: A woven plastic or organic mat that is used heavily in civil engineering applications. Uses include a filter between soil layers of different grain size, increasing shear strength in pavements, embankments, dams and erosion control.

Ice core: A dam core constructed of solid ice and kept frozen throughout the year.

Solifluction: The slow downslope movement of water-saturated sediment due to recurrent freezing and thawing of the ground, affected by gravity.

Frost susceptible soil: Soil that is likely to increase in volume during the freezing process due to ice formation. As a rough approximation, soils having more than 10% of material passing the #200 sieve may be assumed to be frost susceptible (Barker & Thomas 2013).

Zoned earth dam: A type of dam comprised of an impermeable core and one or a number of outer layers of granular material to provide mass and protection to the core. The core is often separated from the outer layers by a filter layer. When the core is composed of clay or till, also referred to as a composite dam.

CHAPTER 1 - Introduction

1.1 Overview

Designing and constructing earth dams in seasonally cold regions brings a number of challenges associated with both the harsh winter conditions and the freeze-thaw cycles throughout the year. Large temperature variations can have a significant effect on the material used in the structure and adequate measures must be taken to ensure that the structure can withstand the impact of the freeze-thaw weathering process. Engineers must also take into account seasonally limited construction schedules and adapt their methods to ensure that the dam is built properly under winter conditions. Standardised design methodology and construction techniques are not readily available to engineers in many of these regions resulting in a variety of adopted practices and design parameters.

The need for a standardised set of guidelines was identified as a way of promoting and optimising design techniques and construction methods in these regions. Although a rigorous quality control process including consensus on each recommendation is required before such guidelines can be used in practice, an investigation that could identify and potentially provide some guidance on issues associated with this area was seen as a worthwhile endeavour and has become the subject of this research project.

The concept of the project was to investigate various practices outlined in the currently available literature from around the world and combine this with practical experience from engineers in the field involved with earth dams in seasonally cold regions. The key areas focused on were design principles, material selection and construction methods.

Independent research has shown that soil behaviour under freeze-thaw conditions is of significance to engineering design of dams. It is widely recognised that many soils undergo physical and mechanical property changes when subjected to freeze-thaw cycles. Fine grained soils such as clays exhibit far more pronounced variations and have shown significant reductions in shear strength and permeability under these conditions.

New methods of stabilisation techniques using soil additives are emerging along with incorporation of geotextiles and membranes which can have a significant impact on dam costs and wall thickness. Material selection and design of the dam structure to inhibit deterioration are critical factors in ensuring that water retaining structures remain structurally and hydraulically sound during repeated temperature weathering cycles.

Poor construction methods in seasonally cold regions can also result in undesirable characteristics in the dam such as formation of ice lenses, piping effects, excessive settlement and voids and loss of critical bearing capacity of the up and downstream faces. Both the seasonal timing of the construction sequence and the quality control implemented during key stages such as compaction and key preparation can have huge consequences and lead to significant dam deterioration problems and even failure.

Although touched upon, this paper does not address issues such as dam feasibility, siting, purpose, risks of collapse, social impact, seismic effects, hydrology or spillway/weir design. There are numerous publications available addressing these issues and this paper is intended to build and expand on the already robust understanding of earth dam design without repeating well understood theory.

1.2 Project Objectives and Scope

The objective of this research project is to identify a range of design and construction issues and provide a set of functional recommendations that might be used as a basis for developing formally adopted guidelines used by engineers asked to undertake design of earth dams in seasonally cold climate regions.

The scope of the project covers embankment design principles, material selection and construction methods for earth dams in cold regions but does not encompass environmental, hydrological, seismic, economic or social aspects. Monitoring recommendations, advanced spillway design and appurtenances are also outside the scope of this project.

1.3 Limitations

Given the time and resource limitations of an undergraduate research project, the research and recommendations in this paper relate primarily to North America, with limited research literature from other cold climate regions such as Sweden and Russia. The author’s personal experience with dam design is also limited to tailings dams and small water storage basins on mine sites in northern Quebec.

1.4 Methodology

The approach taken in order to achieve the objective of the research project involved a number of steps as outlined in Figure 1.1.

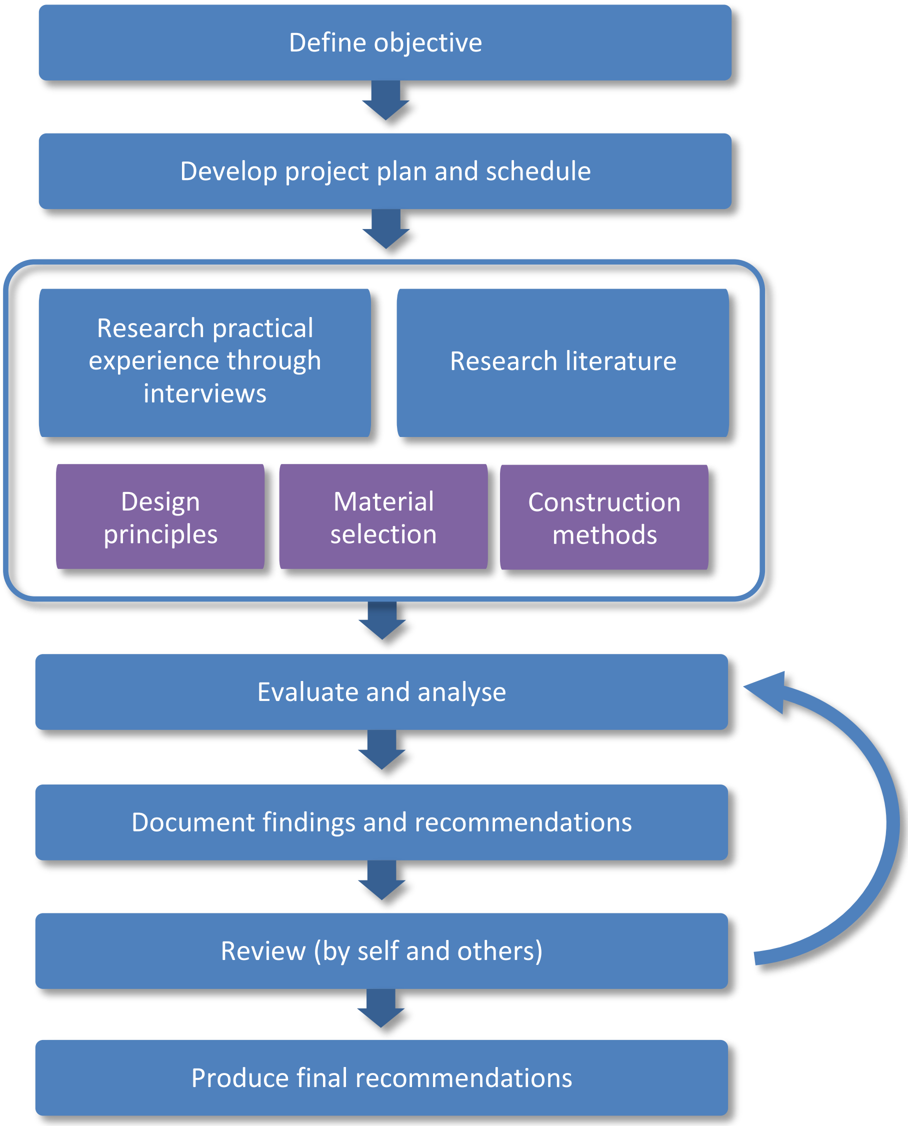


Figure 1.1: Methodology flowchart

The primary areas of design principles, material selection, and construction methods were addressed in separate sections of the project however the process of gathering information from both literature and experienced engineers often overlapped in these areas. Techniques, methods and opinions were evaluated and analysed as part of the quality control process.

1.5 Background

1.5.1 Earth Dams

A dam is defined as a barrier that impounds water for any reason and is classified according to its structure, purpose and size. The International Commission on Large Dams (ICOLD) classifies dams constructed of concrete, stone or other masonry as gravity, arch or buttress dams. Dams built of earth, rock-fill or a combination of these are called embankment dams and represent around 70% of dams worldwide.

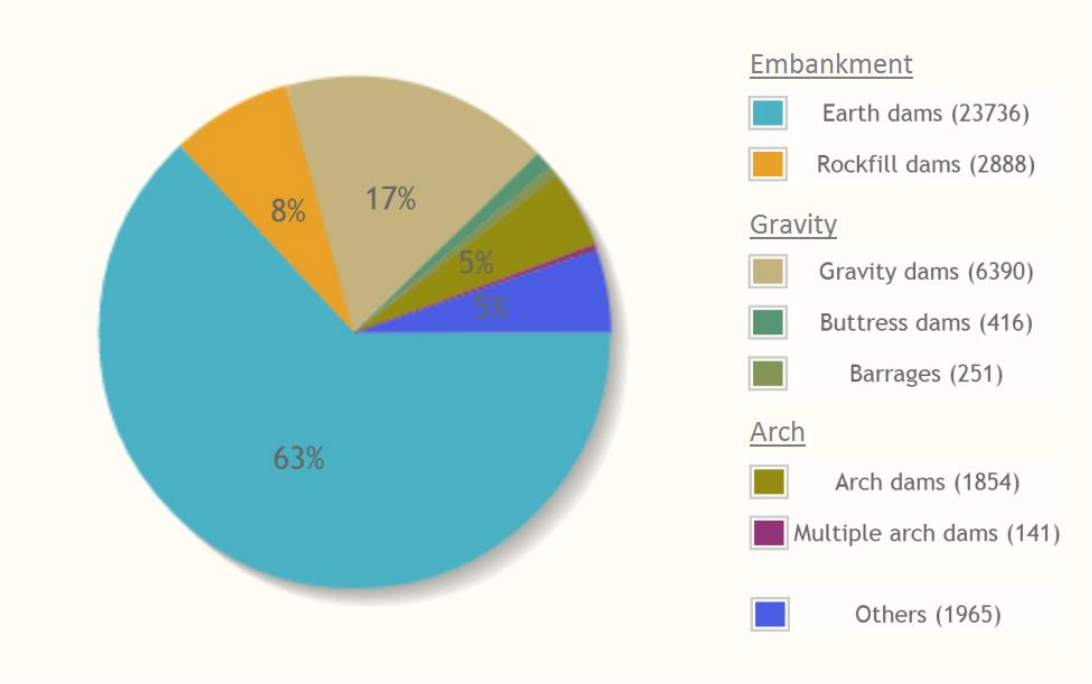


Figure 1.2: Distribution of dam types worldwide (ICOLD)

The most recent publication of the World Register of Dams (ICOLD) puts the single most common purpose of dams as irrigation (50%) followed by hydropower (18%). Many dams are also built for a combination of these purposes.

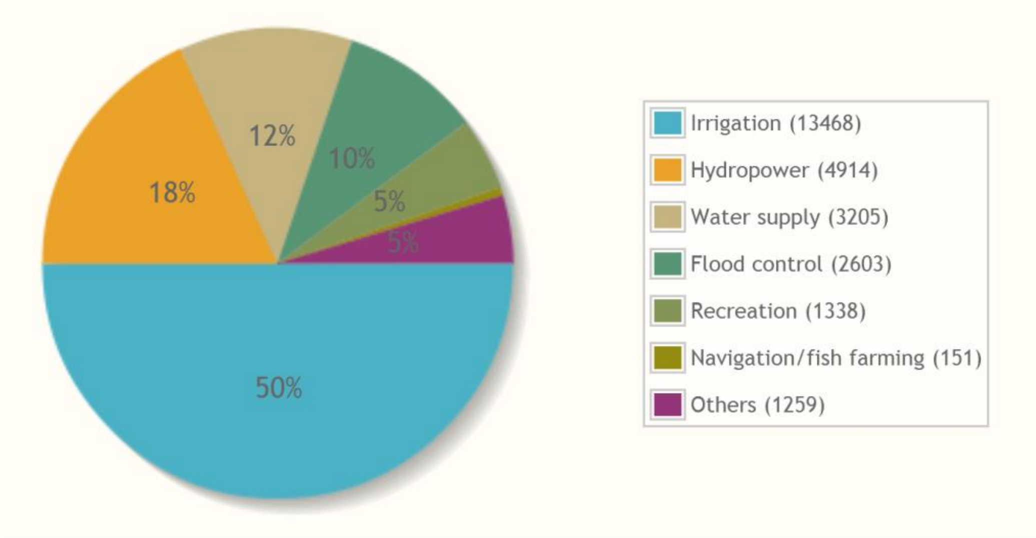


Figure 1.3: Distribution of dam uses worldwide (ICOLD)

The final categorization of dams is based on their size and although no official definition exists, the ICOLD website defines a large dam as:

- Any dam greater than 15m in height
- Between 10m and 15m in height and greater than 500m in length, retaining more than 1,000,000 m^3 of water or with a flood discharge greater than 2,000 m^3/s

By default, this gives the definition of a small dam as any dam that does not qualify as a large dam.

The Canadian Dam Association (CDA) also defined a dam in their Dam Safety Guidelines (2007) as:

- A barrier which is constructed for the retention of water, water containing any other substance, fluid waste, or tailings, provided the barrier is capable of impounding at least 30,000 m^3 of liquid and is at least 2.5 m high.
- Dams less than 2.5 m high or with an impoundment capacity less than 30,000 m^3 if the consequence of dam operation or failure are likely to be unacceptable to the public, such as:
    i. Dams with erodible foundations that, if breached, could lower the reservoir more than 2.5 m; or
    ii. Dams containing contaminated substances.

Structures smaller than the CDA guidelines definition are classified as ‘other’ structures.
Using these two definitions, a reasonable categorization of a small and large dam can be formed.

This paper concentrates on both large and small earth embankment dams (commonly known as earth dams) but also applies to rock-fill embankment dams which include earth as core material. Earth dams can be anything from a simple homogenous earth embankment to a composite or zoned dam. Most embankment dams also feature some sort of drainage layer to collect seepage and usually incorporate a spillway or weir to control excess discharge. A composite dam is the most common type of embankment dam configuration and features an impermeable core and one or a number of outer layers of granular material to provide mass and protection to the core. The core is often made of clay or till and is usually separated from the outer layers by a filter layer to prevent the fine grained core material being eroded via seepage.

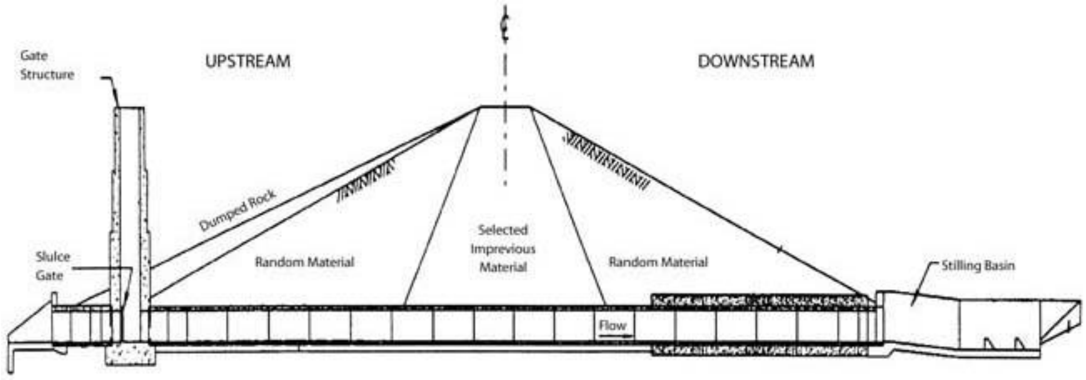


Figure 1.4: Typical cross section of a simple composite embankment dam (source: ICOLD website)

In some cases, an impermeable membrane may be used in place of the clay core, usually located on the upstream face with a layer of material to protect the membrane. An interesting type of variation on an earth dam occasionally used in high latitudes is the *frozen-core dam*, in which a coolant is circulated through pipes inside the dam to maintain a watertight region of permafrost within it. *Tailings dams* are also examples of earth dams, however the material used to construct and raise these is generally the tailings waste material from mining operations in conjunction with a clay core or liner.

Earth dams are the oldest type of dam and the most common due to being very economical to construct on soil foundations, particularly if the material for the embankment is conveniently accessible. The ability to use locally available soil makes them highly desirable in remote regions where the cost of producing or bringing in concrete would be prohibitive. Although certain construction techniques and material selection criteria are required for successful earth dam design, a high degree of skill or expertise is not needed for embankment dam construction and the construction is carried out wholly by earth moving equipment.

1.5.2 Civil Engineering in Cold Regions

The design and construction of civil structures in cold and seasonally cold climates brings a set of challenges not normally faced in temperate regions. ‘Cold regions’ as applies to engineering are defined as locations outside the 0^{o}C isotherm (mean temperature of 0^{o}C during the coldest month of the year) and subject to seasonal frost penetration of at least 300mm once in 10 years (Barker & Thomas 2013). Cold regions are typically subdivided on the basis of whether the ground is only seasonally frozen, whether permafrost occurs everywhere (continuous), or whether permafrost occurs only in some areas (discontinuous). The division between seasonally frozen ground and discontinuous permafrost is approximated by the -5 ^{o}C isotherm with seasonally frozen regions including large portions of North America, Europe and Asia. It is generally assumed that the mean annual ground surface temperature must be below about -3°C for permafrost to exist (Andersland & Ladanyi 2004). Also worth noting is the effect of climate change on permafrost areas, with the prediction that seasonally cold regions will become more widespread.

For construction of earthen structures in these regions, consideration must be given to unique issues such as:

- the effect of the temperature variation on the materials in the structure throughout the design life,
- the potential for extreme climatic events,
- the logistics needed for limited seasonal construction periods,
- high quality control measures for construction to ensure structures will not deteriorate with seasonal freeze-thaw.

Construction methods may need to be adapted specifically for the region, especially where the site may be remote or in inhospitable terrain. Seasonal access to the site may be a large factor in how the construction is planned and executed.

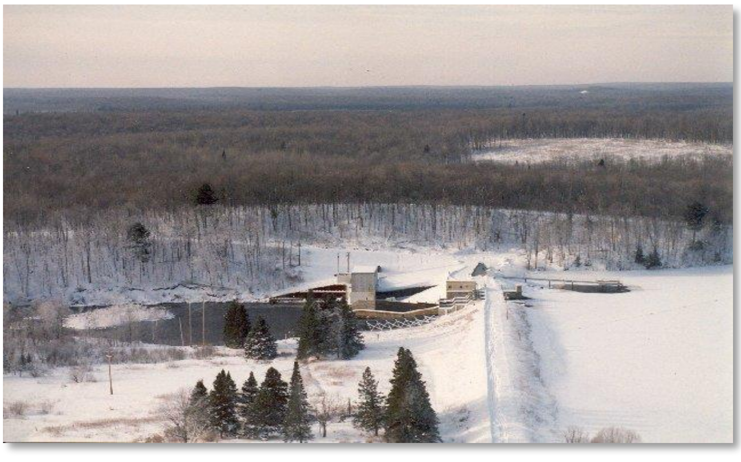


Figure 1.5: Chippewa dam and hydroelectric system during winter

1.5.3 Current Standards and Guidelines for Earth Dam Design

There are a number of existing governmental and non-governmental organisations that provide standards, guidelines and other technical publications for the design of dams. Although each country and region generally has local requirements for dam construction, general dam design and construction guidelines are often not as accessible as guidelines for other infrastructure, such as road, rail or urban drainage.

The International Commission on Large Dams (ICOLD) is a non-governmental International Organisation that primarily acts as a central point for experts from different countries to share ideas, knowledge and experience in dams. The commission also organizes regular symposiums and congresses in addition to publishing technical bulletins on specific dam related subjects written by experts. National Committees from 95 member countries including the Australian National Committee on Large Dams (ANCOLD) and the Canadian Dam Association (CDA) form the arms of this organization and help to facilitate up to date advances in dam design throughout the member countries. Other bodies that have published widely recognised guidelines for earth dam design are the United Nations Food and Agriculture Organisation and the US Army Corps.

Figure 1.6: International framework of ICOLD member country dam committees

There have been a number of publications addressing the design of dams in cold climates, such as the technical bulletin ‘Dams and Related Structures in Cold Climate – Design Guidelines and Case Studies’ (ICOLD 1996), however the format of this bulletin and similar works is very technically specific and does not present a clear and functional guide or a summary of considerations. Another bulletin published by ICOLD titled ‘Embankment Dams on Permafrost – A Review of the Russian Experience’, mentioned embankment and foundation thaw but did not extend to cyclic patterns. Cold climate bulletins tend to focus on permafrost and other perennially cold climate effects, whereas the effect of freeze-thaw cycles is seldom mentioned.

Other publications that are relevant to engineering in cold regions are the Journal of Cold Regions Engineering (published by the American Society of Civil Engineers), technical reports published by the US Army Corps of Engineers Cold Regions Research and Engineering Laboratory (CRREL).

1.6 Summary

The project will generally take the form of an engineering document preparation process, where existing and current knowledge on the subject matter will be combined with real life professional experience and objective opinion and incorporated into a clear, concise set of recommendations. The investigation will concentrate on embankment design and construction aspects of earth dams in seasonally cold regions without becoming too broad in scope. Although other aspects such as environmental, economic, social, seismic and hydrological are recognised as being integral in the design process of most dams, they are not included in order to keep the project focused.

CHAPTER 2 - Literature Review

2.1 Introduction

To provide a platform for the objectives of this paper, a comprehensive review was undertaken to establish the body of literature and practical knowledge currently available relating to design and construction of earth dams specifically in cold and seasonally cold climate regions. The literature review was focused on three key areas:

1. Design Principles
2. Material Selection
3. Construction Methods

Relevant literature was sourced from online databases, websites and suggestions from engineers contacted as part of the project. A number of technical bulletins were also purchased from ICOLD for use in referencing. With the use of the internet, literature was able to be easily sourced from databases containing published work from international sources including Canada and the United States in addition to non-english speaking regions such as China, Russia, Europe through translated papers.

It should also be noted that many countries that have made significant contributions to this field of knowledge but have not published papers in English were not regarded in the research process due to the time and resource constraints of organising translation.

2.2 Design Principles

2.2.1 General Design Concepts

Earth dams are the oldest and simplest type of dam and require less technical expertise than dams such as gravity or arch dams, however it would be a mistake to assume that little skill is required to construct a successful embankment dam. Many aspects of the design and construction process require an understanding of geotechnical concepts and the consequences of slippage or failure.

The United States Society on Dams (USSD) outlines some good underlying concepts for successful earth dam design in its publication 'Materials for Embankment Dams' ((USSD) 2011) which are relevant to dams in all climates. The primary concepts presented in this paper are summarised below.

- **Design defensively, using redundant systems.** For example, a well designed and constructed core, facing or internal membrane backed up by appropriate filters, drains and transitions with sufficient capacity to safely accept flow from cracks or other defects. The many failures and accidents caused directly or indirectly by leakage and piping within the dam, the foundation or the abutments point to the necessity of multiple lines of defence.

- **Use experience and conservative judgment in selecting foundation preparation and treatment procedures.** The only appropriate opportunity to treat the foundation is when it is exposed during construction. It is difficult, expensive, and sometimes impossible to further treat the foundation after much of the embankment has been placed or after the reservoir has filled.
- **Continually review and change, if necessary, the design of the dam.** This process starts during the first reconnaissance of the site and continues through detailed design, construction, reservoir filling and project operation. The owner of the dam must understand that it is not possible to eliminate all uncertainties that could affect construction and the final cost. The design of the dam may need to be modified as the design process proceeds and the design team evolves a better understanding of material and foundation properties.
- **Seek peer review throughout the planning, design and analysis, construction, and operation of the dam and reservoir.** Most large dam constructions require an independent board of consultants to advise the owner with respect to the hydrologic and structural safety of the dam and reservoir from the start of planning studies to project start-up and operation. State dam safety agencies require compliance with specific standards for design and construction. Commonly, on major international projects, an independent panel of experts meets periodically to provide experience and judgment concerning critical design and construction issues regarding foundation treatment, materials, and lines of defence.
- **Throughout the life of the project, evaluate the performance of the dam and reservoir using visual observations and instruments.** Detailed inspections, conducted regularly by walking the crest, slopes, toe and abutments of the dam, provide a visual record of performance. Evaluation of instruments that measure water pressure, seepage rate and deformation provides additional insights concerning performance. Frequent inspections and data evaluation provide the means to judge the performance and structural health of the dam and its foundation.
- **Undertake remedial treatment promptly and in advance of a serious incident.** Any abnormal performance of the dam, the foundation or the abutments, as observed during the visual inspections or as a result of data analysis, must be evaluated to determine the potential impact to the safety of the dam. If it is determined that the safety of the dam may be compromised, the design and construction of remedial repairs should be undertaken immediately.

These guidelines are a solid foundation, however they are purposefully non-specific and do not present any technical recommendations for dam design.

The US Army Corps of Engineers also publishes the “General Design and Construction Considerations for Earth and Rock-Fill Dams” which gives some good clear guidelines for the design and construction of both small and large earth dams. The engineering manual gives a clear definition of an earth dam, its composition and method of construction which is summarized below.

An earth dam is composed of suitable soils obtained from borrow areas or required excavation and compacted in layers by mechanical means. Following preparation of a foundation, earth from borrow areas or required excavations is transported to the site, dumped, and spread in layers of required depth. The soil layers are then compacted by tamping rollers, sheepsfoot rollers, heavy pneumatic tired rollers, vibratory rollers, tractors, or earth-hauling equipment. One advantage of an earth dam is that it can be adapted to a weak foundation, provided proper consideration is given to thorough foundation exploration, testing, and design (USACE 2004).

The manual also outlines the following basic criteria for earth dams to be deemed satisfactory.

- The embankment, foundation, and abutments must be stable under all conditions of construction and reservoir operation including seismic.
- Seepage through the embankment, foundation, and abutments must be collected and controlled to prevent excessive uplift pressures, piping, sloughing, removal of material by solution, or erosion of material by loss into cracks, joints, and cavities. In addition, the purpose of the project may impose a limitation on the allowable quantity of seepage. The design should consider seepage control measures such as foundation cutoffs, adequate and nonbrittle impervious zones, transition zones, drainage blankets, upstream impervious blankets, and relief wells.
- Freeboard must be sufficient to prevent overtopping by waves and include an allowance for the normal settlement of the foundation and embankment as well as for seismic effects where applicable.
- Spillway and outlet capacity must be sufficient to prevent overtopping of the embankment.

2.2.2 Earth Dam Configurations

Embankment dams generally fall into one of the following configurations.

1. Homogenous earth dam
2. Dam with earth core
3. Dam with asphalt concrete (AC) core
4. Dam with upstream facing of asphalt, concrete or geomembrane
5. Frozen core dam

Homogenous Earth Dam

This configuration is generally limited to smaller dams especially in rural applications where the entire embankment can be constructed of a low permeability soil and erosion/slippage has minimal consequences to the downstream regions. These dams can also incorporate filters to control seepage as illustrated in Figure 2.1.

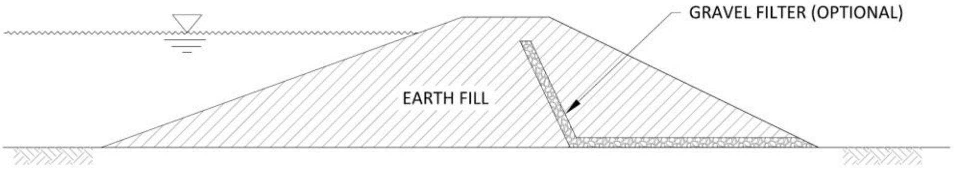


Figure 2.1: Typical cross section of a simple homogenous earth dam

Dam with Earth Core

This configuration is often referred to as a 'zoned' or 'composite' earth dam and features an earth fill embankment that may contain a number of zones of different materials. The core can be centrally located or inclined as shown in Figure 2.2 and can be composed of any suitable material that can act as an impermeable barrier (refer to section 2.3 of this paper for material selection). Natural and compacted clays, glacial tills and silts are the most common core materials. A filter is often used at the interface between two materials of different grain sizes, to help prevent internal erosion and fine grains being carried away through coarse fill. Milligan (2003) highlighted the importance of adequate filters and claims that there have been no incidents of adverse seepage in any embankment dams, even with cores of till, where a sand-rich downstream filter of adequate dimensions has been used.

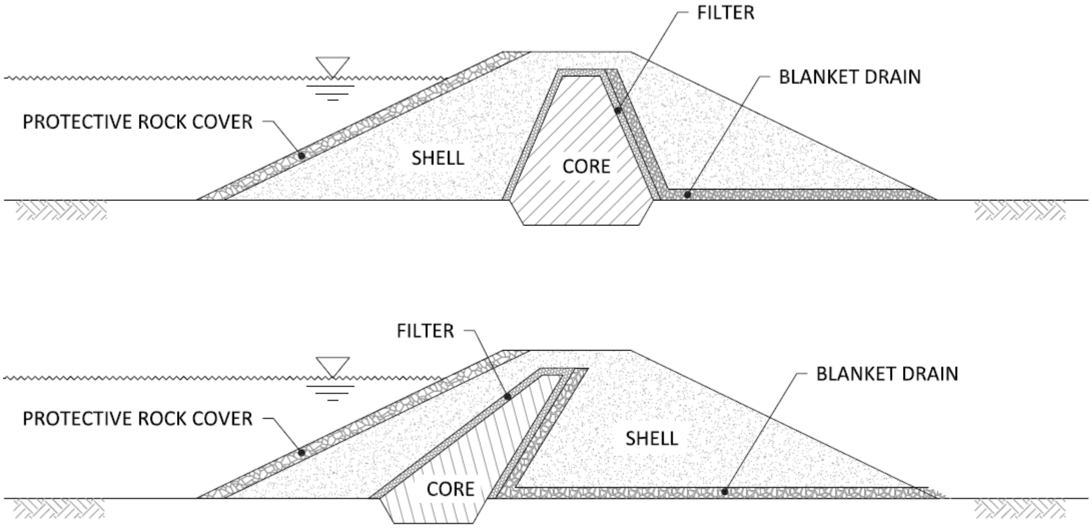
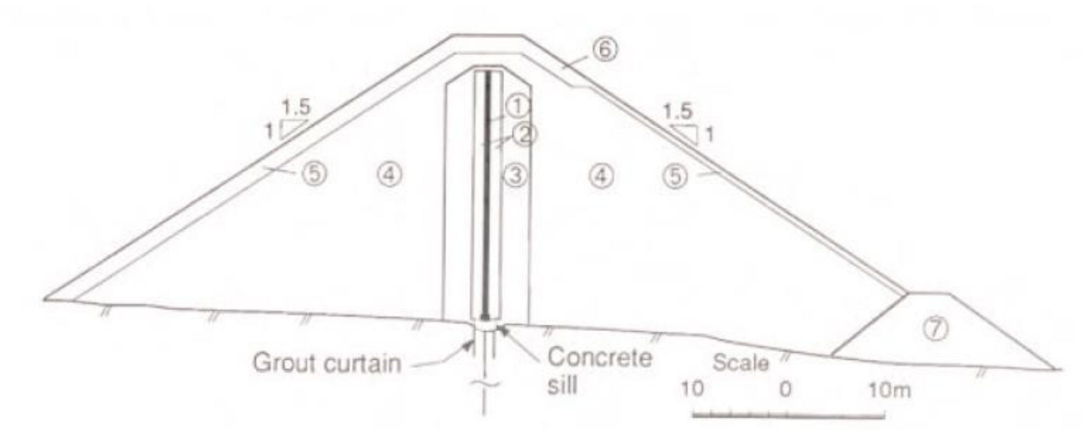


Figure 2.2: Typical cross sections of dams with earth cores

Dam with Asphalt Concrete (AC) Core

These dams feature an outer embankment of earth or rock fill supporting a thin core wall of asphalt or concrete acting as the water barrier. Typically, the vertical or sloped asphalt concrete core wall may be between 0.5 and 1.0 m wide, depending on the height of the dam, seismicity of the site, foundation conditions, and quality of the embankment fill (Wang & Höeg 2011). A more modern approach to AC core dams is to use an upstream transition layer that is grain-size compatible with the upstream shell to serve as a crack stopper for the AC core and a downstream drainage layer to function as a chimney drain ((USSD) 2011). It should be noted that this approach has been questioned by Høeg (1993) in relation so the possible detrimental long term effects and hampering of remediation efforts such as post-construction grouting via drill holes. A typical cross section of an AC core embankment dam is shown in Figure 2.3.



Zone	Material	Layer thickness (m)
(1) Core	Asphaltic concrete (6% bitumen)	0.2
(2) Filter/Transition	Natural gravel or crushed rock, 0-60mm	0.2
(3) Transition	Crushed rock, 0-200mm	0.4
(4) Shoulder (shell)	Quarried rock, 0-400mm	0.8
(5) Slope protection	Selected large blocks > 0.5m^3	Individually machine placed
(6) Crown cap	Selected large blocks > 1.0m^3	Individually machine placed
(7) Toe drain	Selected large blocks > 0.5m^3	Dumped in lifts up to 4m

Figure 2.3: Typical cross section of an AC core earth dam (Høeg 1993)

It is essential that a seal be established between the AC barrier and the dam foundation and great care must be taken to ensure that there are no weak zones that could rupture. A concrete sill is often used in conjunction with a grout curtain as a foundation for the AC core. An asphalt mastic applied to the concrete sill as shown in Figure 2.4 is a common approach for sealing the core wall.

Figure 2.4: Placement of asphalt mastic on the foundation sill (Høeg 1993)

Dam with Upstream Facing of Asphalt, Reinforced Concrete or Geomembrane

These dams use an upstream barrier rather than a core system which can have benefits such as erosion protection of the upstream face (for asphalt and concrete faced dams) and ease of construction. Concrete and asphalt dam facings are generally on the exposed surface and applied as a thin layer.

Concrete has a tendency to form cracks in larger dams so asphalt has become much more widely used as a facing material due to its flexible nature. Geomembranes are generally laid on the upstream face of the dam and protected by a layer of granular material to reduce punctures and limit exposure to sun and weather.

A typical cross section of a simple embankment dam with upstream facing of geomembrane is shown in Figure 2.5.

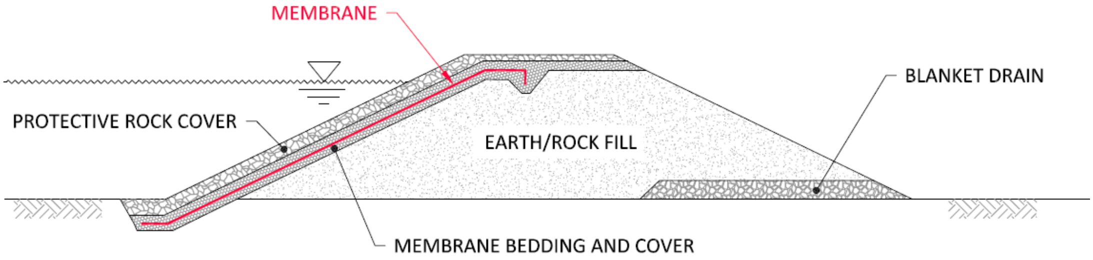


Figure 2.5: Typical cross section of simple earth dam with upstream facing of geomembrane

Frozen Core Dam

This type of dam is typically constructed in high latitudes with permafrost conditions and uses coolant circulating through thermosyphons to maintain a water-tight region of permafrost within the dam core. The advantage is that locally available granular material can be used which is very economical for large remote dams however a high level of monitoring and ongoing maintenance is required to ensure the core material remains frozen.

2.2.3 Internal Filter and Drainage Systems

The importance of filters and drains within earth and rock fill embankments is paramount for a successful dam. The safety of embankment dams depends to large degree on the design, construction, and maintenance of filter and filter/drain systems. Depending on the sources cited, between 30 and 50 percent of embankment dam accidents and failures have involved piping or inadequate drainage ((USSD) 2011).

The primary purpose of an internal drainage system is to lower the phreatic line and dissipate excessive pore water pressures in the downstream portion of the dam increasing the stability of the downstream slope against sliding. The secondary function of these drains is to control any seepage that exits the downstream portion of the dam and prevent erosion of the downstream slope: i.e. to prevent 'piping'. The effectiveness of the drain in reducing pore pressures depends on its location and extent. However, piping is controlled by ensuring that the grading of the pervious material from which the drain is constructed meets the filter requirements for the embankment material. Common configurations such as the chimney or blanket filter/drain systems must be designed to consider the worst case scenario including a cracked core, hydraulic fracturing or core segregation.

Granular filters are designed to prevent migration of soil particles from adjacent foundation or fill materials. Filters are often used in parallel, with layers of varying grain sizes to provide a stepped particle size filtration system. The permeability of a filter or drain must be high enough to avoid excessive pore pressures and as a rule of thumb a simple drain will have at least 100 times the permeability of the fill material ((USSD) 2011). The design of a downstream drainage system is controlled by the height of the dam, the cost and availability of permeable material, and the permeability of the foundation. For low dams, a simple toe drain can be used successfully.

The compaction of filters and drains should also be limited to about 70 percent relative density, to avoid particle breakdown and increased permeability ((USSD) 2011).

The various types of drainage systems include:

- Toe drain
- Horizontal blanket drain
- Chimney drain

2.2.4 Depth of Frost Penetration

Ideally frost penetration depth should be measured directly or based on nearby data as part of the geotechnical investigation of any civil structure built in cold regions however this is sometimes difficult or uneconomical if the site is remote. Estimation of frost depth into various soils has been studied and refined however calculations will only be an approximation and based on highly variable input such as weather data and soil characteristics.

Some of the first studies of freeze-thaw depth were carried out by Josef Stefan in 1889 and based on research work into calculation of the thickness of ice formations on a calm body of water. His equation considers the latent heat, the freezing index in degree-days, and the thermal conductivity and is expressed as shown in Equation 2.1.

$$X_{STEFAN} = \sqrt{48\,K\,nF\,/\,L}$$

where

$X =$ depth of freezing plane (ft)
$K =$ thermal conductivity of soil (Btu/ft hr ^{o}F)
$nF =$ freezing index (degree-days)
$L =$ volumetric latent heat of soil (Btu/ft^3)

Equation 2.1: Stefan Equation for estimating frost depth (Paynter 1999)

It was recognised that the equation did not consider the thermal energy stored as volumetric heat in the soil and therefore tended to overestimate the frost depth in temperate zones. Berggren improved upon this formula in the early 1950s however it was Aldrich and Paynter (1953) that proposed the modified formula still used today which they termed the 'Modified Berggren Equation'. Their formula applied a dimensionless coefficient λ to the depth of frost computed by the Stefan equation to account for the thermal energy stored in the soil.

$$X_{BERGGREN\ MOD} = \lambda \sqrt{48\,K\,nF\,/\,L}$$

where

$X =$ depth of freezing plane (ft)
$\lambda =$ function of thermal ratio α and fusion parameter μ
$K =$ thermal conductivity of soil (Btu/ft hr ^{o}F)
$nF =$ freezing index (degree-days)
$L =$ volumetric latent heat of soil (Btu/ft^3)

Equation 2.2: Modified Berggren Equation for estimating frost depth (Paynter 1999)

Solution of this equation using manual methods is relatively complex and is outside the scope of this paper however there are a number of computer models that have been developed to calculate a solution.

2.2.5 Failure Mechanisms for Earth Dams

An understanding of the causes of failure is a critical element in the design and construction process for new dams and for the evaluation of existing dams. The primary cause of failure of embankment dams internationally is overtopping as a result of inadequate spillway capacity. The next most frequent cause is seepage and piping. Seepage through the foundation and abutments is a greater problem than through the dam. Therefore, instrumentation in the abutments and foundation as well as observation and surveillance is the best method of detection. Other causes are slides (in the foundation and/or the embankment and abutments) and leakage from the outlet works conduit. In recent years, improved methods of stability analyses and better tools for site characterization and obtaining an understanding of material properties have reduced the frequency of failures from sliding stability (USACE 2004).

Figure 2.6: Failure of the Teton Dam in 1976 due to piping effects

The process of internal erosion of the embankment or foundation caused by seepage is known as piping. Generally, erosion starts at the downstream toe and works back toward the reservoir, forming channels or pipes under the dam. The channels or pipes follow paths of maximum permeability and may not develop until many years after construction.

Seepage is the continuous movement of water from the upstream face of the dam toward its downstream face. The upper surface of this stream of percolating water is known as the phreatic surface. The phreatic surface should be kept at or below the downstream toe.

2.3 Material Selection

Earth and rock fill dams are constructed of all types of geologic materials, with the exception of organic soils and peats. Most embankment type dams are designed to utilise the economically available on-site materials for the bulk of construction. Special zones such as filters, drains and riprap, may come from off-site sources. Soil materials used in embankment dams commonly are obtained by mass production from local borrow pits, and from required excavations where suitable ((USSD) 2011).

Core material in zoned earth dams is an especially critical area as poor material selection can lead to seepage, piping or failure. The most common material for earth dam cores is clay or glacial till as they are usually the most economical to source. Both of these materials are frost susceptible owing to their fine grained structure and therefore if they are used in cold regions care needs to be taken to ensure they are well insulated from frost action.

Asphaltic concrete (AC) cores can also be used as the barrier in earth dams. AC is able to move and flex with settlement and is well suited for use in situations where freezing and thawing may cause movement of the core, in addition to being impervious to the effects of frost. An alternative to the embankment core configuration is to use geomembranes or geosynthetic clay liners (GCLs) to provide a film barrier on the upstream slope. For situation where winter construction is necessary, geomembranes offer a cost effective and practical alternative to the problematic laying and compaction of fill in freezing conditions.

2.3.1 Fine Grained Soils

Fine grained soils (primarily clays and silts) are commonly used as construction material in homogeneous earth dams and impervious core sections of zoned embankment dams. They are defined as materials having at least 50 percent by weight of particles finer than 0.074 mm, or the openings of a Standard No. 200 sieve, according to the Unified Soil Classification System (USCS). Inorganic, fine grained soils are classified as either clays or silts. Clays and silts typically exhibit different engineering behaviour with regard to compressibility, strength and permeability ((USSD) 2011).

A widely used and important geotechnical indexing system for fine grained soils is the Atterberg limits, which helps geotechnical engineers classify and characterise fine grained soils according to the degree to which moisture changes impact soil consistency and behaviour. The two primary tests are the liquid limit (LL) and the plastic limit (PL) tests which are used to measure the water content at the transition between liquid/plastic states, and the lower limit of the plastic state respectively. These limits can then be used to determine the plasticity index of the soil. Test procedure steps are illustrated in Figure 2.7.

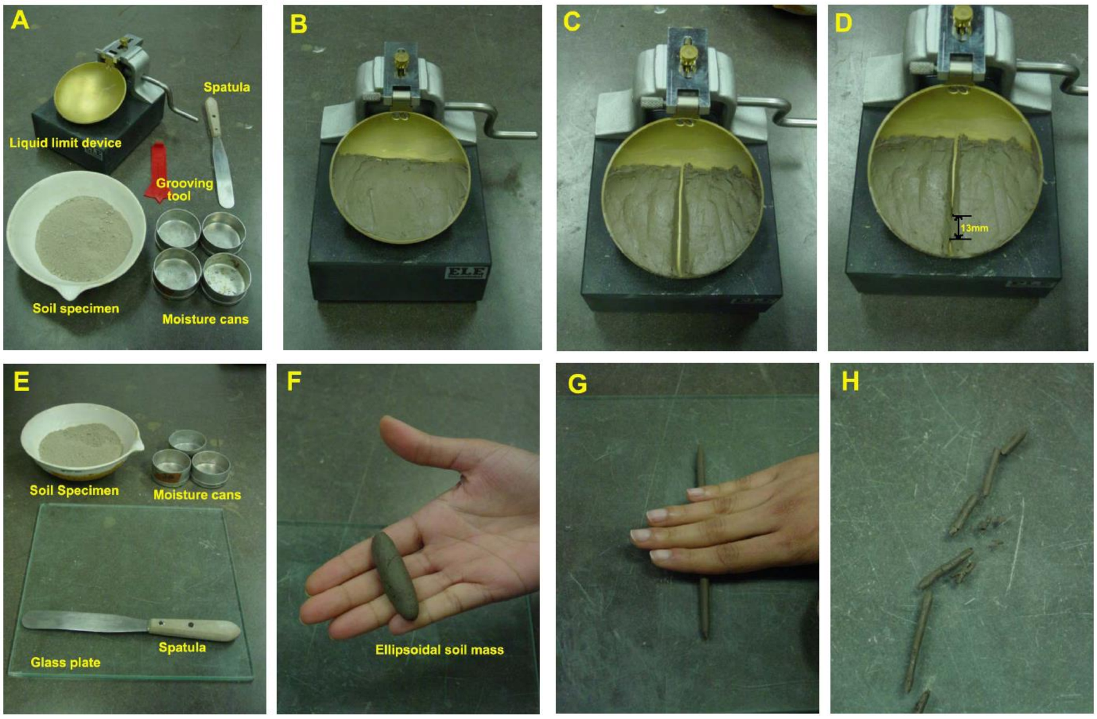


Figure 2.7: Atterberg Limit Test Procedure Steps (source: www.uic.edu)

Use of fine grained soils in embankments must be undertaken with extreme care, studies by Sherard (1953) found the correlation between the fineness of soil and the susceptibility to sliding outweighed all other factors including slope, construction methods and reservoir activity ((USSD) 2011). In most cases, zoned earth dams will be built with a core zone of impervious fine grained soils flanked by zones of higher strength materials for reasons of safety and economy.

Placement moisture of fine grained material will have a significant effect on the compressibility of the dam in areas of low consolidation stress, such as in the top of the dam. Material placed too far below standard proctor optimum moisture content (as determined by ASTM D698) may develop settlement or collapse upon wetting. Gradation and plasticity of embankment soils are considered to be more important than placement moisture conditions under high consolidation pressures, such as in the lower portions of a high dam (Sherard et al. 1963).

Dispersive clays are characterised by highly erodible behaviour caused by a high percentage of sodium in the clay, which is easily dissolved into seepage water and carries fine clay particles with it as it disperses. This type of clay should generally be avoided in dam embankment construction, however if economic factors govern material choice, special measures can be implemented including proper filters (ICOLD 1990).

2.3.2 Coarse Grained Soils

Coarse grained soils (primarily sands and gravels) are primarily used in structural fill zones (or shells) and in specialty filter and drain zones within embankment dams. Coarse grained soils can also be used in core zones, especially when the fines content is greater than 20 percent.

Coarse grained soils are defined by the USCS as those materials having more than 50 percent by dry weight of particles retained on the Standard No. 200 sieve, or 0.075 mm. Coarse grained soils include gravels and sands, which are distinguished between by grain size. Sands are defined as soils finer than the No. 4 sieve (4.76 mm) and coarser than the No. 200 sieve. Gravels are coarser than the No. 4 sieve and finer than 76.2 mm ((USSD) 2011).

Clean sands and gravels, meaning sands and gravels that have less than about 5 percent fines by dry weight are pervious, easy to compact, and are minimally affected by changes in moisture. The important properties of interest in embankment dam engineering, namely shear strength, compressibility, and permeability are determined by the gradation, grain size and shape, relative density, and durability of the coarse grained soil. Clean sand and gravels have high hydraulic conductivity (or permeability) which is directly related to grain size using the Hazen equation ((USSD) 2011). This relationship is most obviously exploited in the design of filters and drain zones for zoned embankment dams.

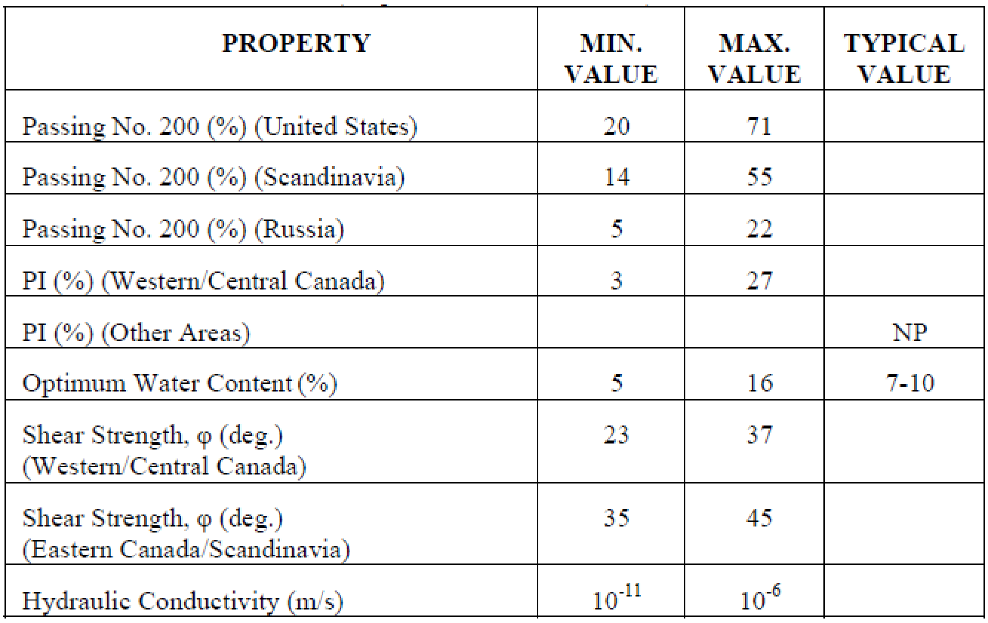
Clean sands and fine gravels tend to be highly vulnerable to surface erosion under wave action and surface runoff. These materials generally are not used on the outer slopes of embankments and are often protected by properly bedded riprap, coarse gravel, or rock blankets.

Loose saturated sand is also vulnerable to liquefaction which can lead to flow slides and embankment failure.

2.3.3 Broadly Graded Soils

Many natural soil deposits comprise a large range of particle sizes, and their engineering behaviour is intermediate between fine grained and coarse grained soils. Broadly graded (or well graded) soils typically exhibit properties of low hydraulic conductivity, high shear strength and low compressibility in comparison with fine grained soils. These engineering properties make them of particular interest to dam engineers.

In the northern hemisphere, large areas of land contain deposits of glacial till (or moraine) left behind by glacial action. Glacial till is a very widely used, economic and useful material for embankment dam construction although geotechnical investigation is sometimes required to identify sources that are not contaminated by lateral debris before the material can be used directly. Engineering properties of till suitable for use in embankment dams is shown in Table 2.1, adapted from ICOLD (1989).



PROPERTY	MIN. VALUE	MAX. VALUE	TYPICAL VALUE
Passing No. 200 (%) (United States)	20	71	
Passing No. 200 (%) (Scandinavia)	14	55	
Passing No. 200 (%) (Russia)	5	22	
PI (%) (Western/Central Canada)	3	27	
PI (%) (Other Areas)			NP
Optimum Water Content (%)	5	16	7-10
Shear Strength, φ (deg.) (Western/Central Canada)	23	37	
Shear Strength, φ (deg.) (Eastern Canada/Scandinavia)	35	45	
Hydraulic Conductivity (m/s)	10^{-11}	10^{-6}	

Table 2.1: Engineering Properties of Till Materials Used in Embankment Dams (ICOLD 1989)

The grain size distribution of till varies across different regions and grain size distribution analysis is generally carried out before a till material is used for construction. An example grain size distribution for a till from Northern Quebec is shown in Figure 2.8. Tills are often classed as low or high plasticity, based on the percentage of fines in the soil. Low plasticity till is generally preferred for construction material however often hauling distance will be the deciding factor on whether local till is used or not.

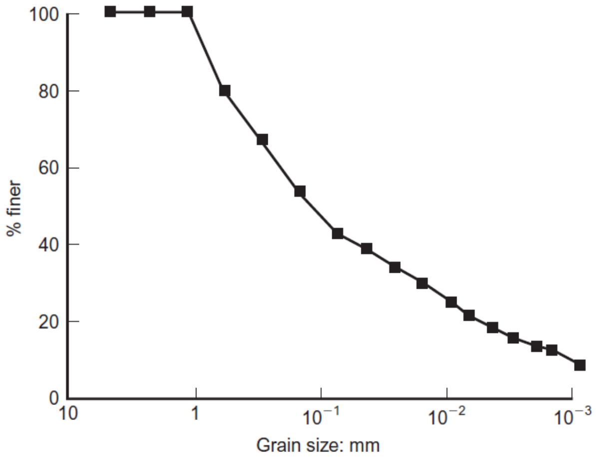


Figure 2.8: Grain size distribution of Peribonka glacial till (Konrad 2010)

Broadly graded soils offer good characteristics for core material however special attention needs to be taken with the downstream filter system to defend against internal erosion and piping. Core width, adequate filter zones and material selection and mixing are extremely important design issues for these types of materials.

2.3.4 Behaviour of Soils under Freeze-Thaw Conditions

The behaviour of soils undergoing cycles of freeze-thaw has been well studied and a number of papers and articles have published reporting on the results of various laboratory and field tests. Of particular interest to embankment dam design are the changes in permeability, strength and volume measured in fine grained (clays) and broadly graded (till) soils. These soils are classed as “frost susceptible” as they are likely to increase in volume during freezing in the presence of sufficient water. Factors affecting the frost susceptibility of soils include capillary rise and permeability. As a first approximation, soils having more than 10% of material passing the #200 sieve may be assumed to be frost susceptible (Barker & Thomas 2013). Frost susceptible fill material may be exposed to frost heave, where freezing temperatures advance into frost-susceptible soil in the presence of an abundant water supply. Heaving action occurs when water migrates into the freezing front (layer of soil where freezing temperatures start) to form ice lenses, creating ice segregation. Upon thawing, rearrangement of particles takes place and the soil structure is altered. Fine grained soils may therefore exhibit weak zones with reduced shear strength and increased hydraulic conductivity. Internal erosion may start in such weak zones, causing problems that may lead to dam failure (Jantzer & Knutsson 2007).

Effect on Permeability

Most studies on the effect of freezing and thawing on the permeability and structure of soils have concluded that hydraulic conductivity increases after a number of freeze-thaw cycles however the degree of change is affected by both the soil properties and the conditions of the experiment. Chamberlain, Iskandar and Hunsicker (1990) claimed large increases in permeability of up to two orders of magnitude were measured in small samples of compacted clay frozen and thawed in a laboratory. Tests were conducted on five different clays compacted at optimum water content and frozen from bottom to top with free access to water (an “open system” for freeze-thaw). For four of the clays, the hydraulic conductivity increased by up to two orders of magnitude during the first five freeze-thaw cycles and ceased changing after about nine cycles. Chamberlain, Iskandar and Hunsicker (1990) attributed the increases in hydraulic conductivity to macroscopic horizontal and vertical cracks that were formed during freeze-thaw.

Zimmie and La Plante (1990) carried out a similar experiment in a closed system with similar results however they also observed that the initial water content affects the degree of change in permeability. Othman (1992) studied the effect of freeze-thaw on three compacted clays and concluded that the change in hydraulic conductivity was affected by the amount and type of compaction, the initial conductivity of the clay and most notably the temperature gradient during the freeze-thaw process. Chamberlain and Gow (1979) also proposed that fine particles might move out of large pore spaces during freezing and thawing. The most extreme of these findings was a claim that compacted natural clay was found to increase up to 1000 times under freeze-thaw cycling (Chamberlain, Erickson & Benson 1997).

The behaviour of glacial till was also investigated and found to exhibit many of the same characteristics as clay soil when undergoing freezing and thawing. Konrad (2010) concluded that low plasticity glacial till from Northern Quebec increased in permeability after a number of cycles however this was likely to be offset by thaw-induced settlements which tended to reduce the void ratio. This settlement was dependent on the initial void ratio of the material. Investigations by Viklander (1997) showed that the permeability in a fine-grained till typically increased by up to 10 times in an initially dense till and decreased between 1 to 50 times in an initially loose till.

It should be noted that there has been some contention about the effects of freeze-thaw on compacted clays and tills after investigations into the testing methods used for many of the experiments during the early 90s were accused of being not applicable to field conditions. It was alleged that samples measured in the lab were not representative of actual in situ material behaviour and that disturbance of the samples during measurement was affecting the results. Further work by Benson and Othman (1993) on samples frozen and thawed in situ concluded that compacted clay in the field did in fact increase in permeability significantly above the freezing plane and that migrating water caused vertical shrinkage cracks to form up to 150mm below the freezing plane as illustrated in Figure 2.9. The process of soil undergoing freezing is described in the following steps.

1. When air temperature at surface is below freezing, a freezing plane advances into the soil (Figure 2.9(a)).
2. As soil temperature drops below freezing, ice crystals form in the centre of large pores. Water expands by 9% when changing to ice so the surrounding soil is forced to move, rearrange and consolidate.
3. A partially frozen layer, called the frozen fringe separates the frozen and unfrozen soil (Figure 2.9(b)). Thermodynamic processes occurring in the fringe result in pore water suction pressure.
4. The suction pressure creates a hydraulic gradient that draws water up from below the freezing plane and into the freezing zone (Figure 2.9(c)). This migrating water causes a reduction in water content (Figure 2.9(d)) and vertical shrinkage cracks to appear below the freezing plane.
5. Water migrating from below freezes behind the freezing plane and if enough water accumulates, ice lenses will form. It was observed that ice lenses become more widely spaced as the depth increases, with smaller and more frequent ice lenses toward the surface (Figure 2.9(b)).

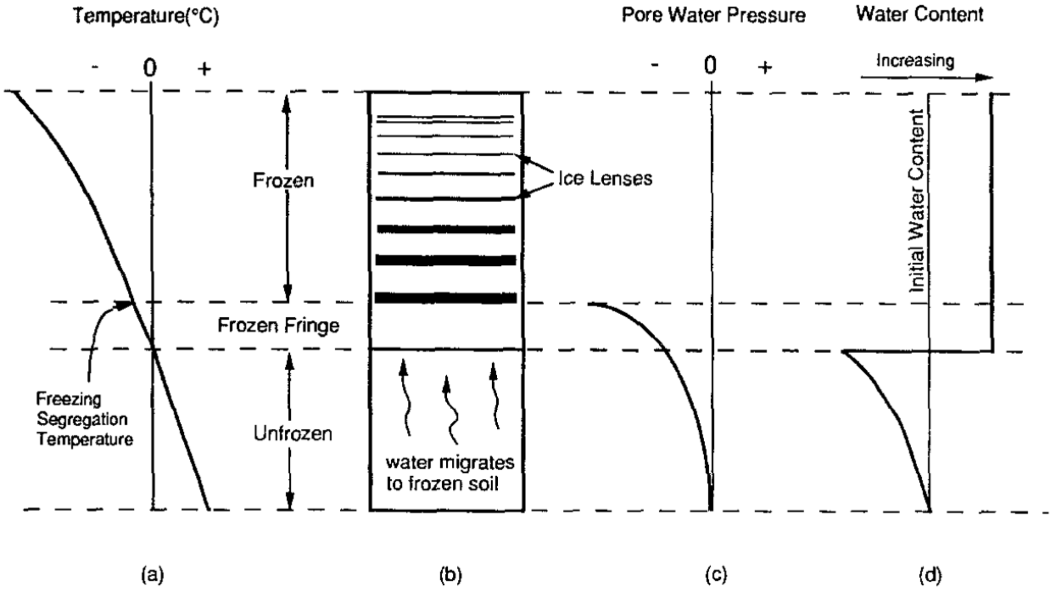


Figure 2.9: Soil freezing in a closed system (Benson & Othman 1993)

Upon thawing, these ice lenses melt away leaving a network of tiny cracks and fissures which results in increased permeability (Chamberlain, Iskandar & Hunsicker 1990).

Effect on Density

Investigations by Viklander (1997) showed that fine grained till exhibited volume changes due to the freeze/thaw cycles and the volume typically decreased for an initially loose soil and increased for a dense soil (Figure 2.10). A residual void ratio was reached after 1-3 freeze/thaw cycles, independent of the state of the soil structure prior to freezing. The residual void ratio ranged from 0.31 to 0.40 in the studied material. Finally, no particle movements were detected, but significant stone movements in vertical as well horizontal direction were identified (Viklander 1997). Similar behaviour was also observed in clays and silty soils (Eigenbrod 1996; Konrad 1989). This phenomena is important to dam design as excessive settlement or heaving could lead to embankment issues.

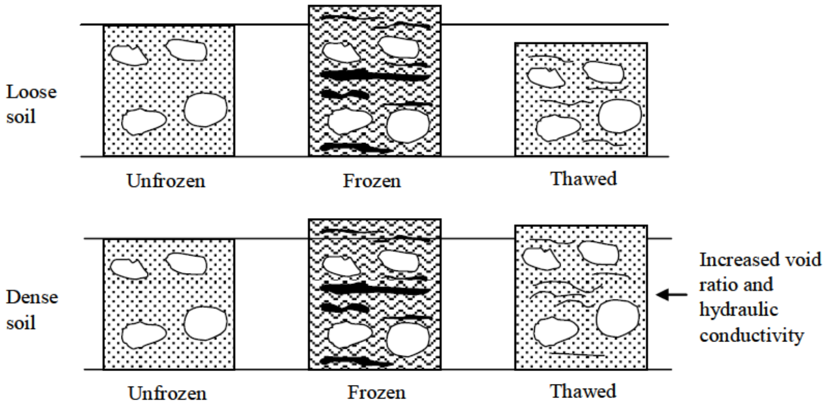


Figure 2.10: Effect on density and void ratio for initially loose and dense soils

Effect on Strength

The effect of freeze-thaw cycles on the mechanical behaviour of clays was investigated by Zhao et al. (2012) by subjecting samples to 31 freeze-thaw cycles and measuring both the unconfined compression (UC) and the unconsolidated-undrained triaxial compression (UUTC) strength at various intervals. It was found that the UC strength was reduced by 11%, elastic modulus by 32% and cohesion by 84% after 31 cycles compared to unexposed soils. The angle of internal friction was also slightly increased. Qi, Ma and Song (2008) investigated the engineering properties of a silty loess soil and found that the preconsolidation pressure and cohesion will increase if the density of the soil is above a critical dry unit weight (γ_d^{cr}) and decrease if it is below the critical limit after one freeze-thaw cycle.

A study of a frost affected hydropower embankment dam in northern Sweden that was exposed to over 30 years of freeze-thaw cycling (Jantzer & Knutsson 2007) found that the glacial till core experienced frost penetration to a depth of between 2 and 5 metres into the core. Field observations confirmed that the material in the affected zone was structurally different from the deeper material, with significant fractures observed in the upper regions of the core (Figure 2.11).

Figure 2.11: Fractured core of till dam at a depth of 0.5m (Jantzer & Knutsson 2007)

2.3.5 Asphalt Concrete (AC)

Asphalt or Asphaltic Concrete (AC) is a composite material composed of bitumen and aggregates commonly used on roads, airfields and increasingly in embankment dam cores. The optimum density for a standard AC core is approximately 6% bitumen mixed with uniformly graded aggregates however mixes with up to 12% bitumen have been used in Russia and Norway to give greater visco-elasticity in low temperatures (Høeg 1993).

Figure 2.12: Core sample of Asphalt Concrete (AC) dam core

Although local clays and tills have generally always been the preferred material used in embankment dam cores based on economy, asphalt concrete has become very attractive in the past decade as a viable alternative in cold, wet or remote regions due to a number of advantages over natural soil including:

- reduced construction time
- the ability to construct in cold and wet conditions
- vicso-elastic adjustment to deformation due to construction or seismic activity
- limited self-healing capacity as cracks develop in core wall (when upstream filter containing fine grained material is used)
- extremely low permeability
- resistance to internal erosion effects experienced in earth cores
- reduced core width
- minimised requirements for filter and drainage systems due to lower seepage
- reduced maintenance requirements

Over 100 asphalt concrete dams have been built worldwide since 1964 and all have shown excellent performance under all climatic conditions (Wang & Höeg 2011). Of special note is its high tolerance to freeze-thaw cycles and resistance to frost.
Comparative studies by Wang and Höeg (2011) at several recent projects have shown the asphalt concrete core option to be very competitive with earth core dams both technically and economically. Dams up to 170m high such as the Quxue dam in China have been successfully constructed using this method.
ICOLD bulletin 84 (1992) presents recommendations related to the use of bituminous cores in embankment dams.

2.3.6 Geomembranes and Geosynthetic Clay Liners

Geomembranes

Geomembranes have become very popular due to advances in technology and the development of composite membrane materials. Geomembranes can be composed of PVC, PE or bituminous materials and are generally laid with a protective cover of granular material over them. Bituminous geomembranes are suitable for use in UV exposed or very low temperature areas and have been shown to provide very good durability for up to 20 years (Breul et al. 2004). They are commonly manufactured and delivered in rolls and seamed on site however some geomembranes have been formed in large panels off site and delivered to the site for installation. They can be thermal readily welded with hot air, hot wedges, or extrusion.

Bituminous materials can be categorized in two broad groups - oxidized bitumen and bitumen elastomer. Both exhibit visco-plastic stress strain behavior and can be readily thermal welded. Oxidized bitumen is significantly affected by high temperatures and has reduced flexibility at low temperatures, whereas the effects are less pronounced in the bitumen elastomers. Bituminous geomembranes are highly resistant to ultraviolet radiation, although the surface may craze if there is no protective layer ((USSD) 2011).

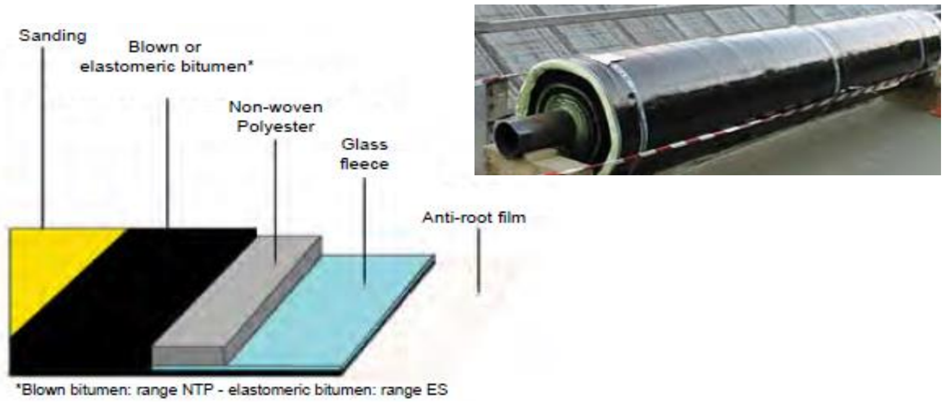


Figure 2.13: Structure of Coletanche bituminous geomembrane and delivery roll (source: www.coletanche.com)

Geosynthetic Clay Liners

A geosynthetic clay liner (GCL) is a woven composite fabric-like material that has similar features to a geomembrane and a geosynthetic and incorporates a bentonite layer which has a very low hydraulic conductivity. As the bentonite or clay comes into contact with moisture, it expands within the geotextile sandwich and creates a water barrier.

Bentonites composed predominantly (>70%) of Montmorillonite or other expansive clays are preferred and most commonly used in GCLs. A general GCL construction would consist of two layers of geosynthetics stitched together enclosing a layer of processed sodium bentonite. Typically, woven and/or non-woven textile geosynthetics are used, however polyethylene or geomembrane layers or geogrid geotextiles materials have also been incorporated into the design or in place of a textile layer to increase strength (Wikipedia). In relation to seasonally cold regions, mineral based geofabrics are not preferred as they are frost susceptible unless adequate insulative cover is provided.

Figure 2.14: Geosynthetic Clay Liner (GCL) being installed on an embankment dam (source: www.geofabrics.com.au)

2.4 Construction Methods

The methods used for earth dam construction vary between countries and regions however all share similar philosophies. Machinery used in the construction process has advanced greatly since early dams were built however the process has remained relatively similar. For an embankment dam, the key areas for construction are:

- Foundation/key preparation
- Placement and compaction of the material
- Installation of drainage/filter systems, membranes and rock protection

2.4.1 Foundation Preparation

The basic premise of a dam is to retain water so it follows that the barrier, whether core, wall or membrane, must be founded on a suitably water tight foundation to prevent water movement under the embankment.
The primary purposes of foundation and abutment treatment are (USBR 1984):

- to provide positive control of underseepage
- to prepare the foundation contact for placement of the overlying compacted fill
- to minimize differential settlements and thereby prevent cracking of the embankment
- to prevent migration of embankment material into fractures or openings in the foundation.

In many cases, the embankment will be constructed over natural ground which could contain layers of soft, organic, fractured, weathered, or otherwise unsatisfactory materials. Foundation preparation involves removal of this material as far as practically possible in addition to grouting any depressions or fractures in the exposed rock surfaces to provide a relatively smooth and uniform base for the core or membrane to connect to.

Figure 2.15: Removal of weathered rock during foundation preparation work (USBR 1984)

Cutoff systems such as grout injection curtains can also be used to treat fractured rock below the impermeable zone of a dam. The depth, number of curtain rows and type of grout depends on the extent of fracture however all injection should be pressure tested with pumped water once completed to ensure adequate filling of cracks.
Injection should be avoided under freezing conditions as ice can form a blockage to any grouting paths through the rock.

2.4.2 Placement and Compaction

Placement and compaction of core, filter and fill material within the embankment should be managed carefully during construction. Mechanical dumping and spreading in lifts of 300mm or less is a proven method of construction with compaction being carried out by some type of roller. The roller will depend on the material being compacted. For clayey/plastic soils a sheepsfoot or tamping type roller (see Figure 2.16) should be used however more silty soils can be handled most effectively by a vibratory padfoot roller. Shell or filter materials of gravel and rock should be compacted using a vibratory, smooth drum steel wheeled roller where possible.

Figure 2.16: Type of sheepsfoot roller used for compacting clayey soils (USBR 1984)

Borrow areas should be free of snow, ice and moisture if constructing during winter. No winter construction of core material should be carried out due to the frost-susceptibility of clays and tills however sands and gravels can be handled effectively even at low temperatures (USBR 1984).

Compaction rates will vary with the material, however a minimum of 95% proctor at optimum moisture should be the target for core material.

2.4.3 Installation of Drainage/Filter Systems, Membranes and Rock Protection

Internal drainage systems and filters should be protected from contamination as much as possible during the construction phase, using geotextile crossings for trucks and machinery. The compaction of filters and drains should be limited to about 70 percent relative density, to avoid particle breakdown and increased permeability ((USSD) 2011).

Geomembranes should be laid in vertical strips down the upstream face of the embankment on a layer of bedding material of sand or similar. An anchor trench should be used at the top of the embankment with at least a 1m thick layer of material burying a 2-3m long length of membrane for stability. A cover of sand or similar material should also be used to cover and protect the membrane, with rock dumped on top to provide protection from waves. No machinery should drive on the membrane during or after construction.

Upstream rock protection should be dumped rock where possible, as this provides the most adaptable and effective solution to settlement or underscour problems due to the concept that the rocks can resettle ((USSD) 2011).

2.4.4 Asphalt Concrete Construction Methods

A proven method of construction for asphalt concrete core embankment dams involves placement and compaction of uniformly graded, crushed stones or pebbles impregnated with bitumen in consecutive horizontal layers 0.2m – 0.3m thick. AC cores are generally only 0.5m - 1.0m wide so small rollers are often used as shown in Figure 2.17 (Høeg 1993).

Figure 2.17: Simultaneous compaction of asphalt concrete core and filters (Høeg 1993)

Asphalt cores are generally laid and compacted as the dam is raised in horizontal lifts of 0.2m to 0.3m for adequate compaction. An example of this compaction method is illustrated in Figure 2.18.

Figure 2.18: Compaction of asphalt concrete (AC) core and filters in AC core rock-fill dam (Høeg 1993)

Figure 2.19: Construction of an Asphalt Core dam in Norway

Metal sheet shuttering is used as formwork along the sides of the core wall as the dam is raised, allowing simultaneous construction of the core wall, filters and shell material (Høeg 1993).

CHAPTER 3 - Practical Experience Review

The objective of this paper is to bring together both the literature and practical knowledge available that relates to design and construction of earth dams and other earth structures in cold climate regions. Practical experience is often far more valuable than results obtained in simulated laboratory experiments however it can be both difficult to gather and subject to opinion rather than factual data. By contacting a range of professionals in the field of geotechnical and civil engineering a number of experiences and opinions were able to be incorporated and weighted for use in the final guidelines. Of significant importance to this section are the case studies that have been described by the professionals interviewed. Case studies are a valuable source of information for analysing and learning how dam designs and construction methods can be improved.

The engineers contacted as part of the investigation for this research project provided a large range of issues experienced, observations and even recommendations which have been grouped into the following sections:

- Settlement and Uplift Issues
- Seepage Issues
- Embankment Deterioration Issues
- Drawdown Related Issues
- Fill Material Issues
- Membrane and Geotextile Related Issues
- Spillway Issues
- Winter Construction Issues

In an effort to keep the focus of the paper on embankment dams specifically in seasonally cold regions, general observations and issues with earth dams in general climates have been kept to a minimum.

3.1 Settlement and Uplift Issues

Many dams and embankments were observed to have differential settlement problems due to both the freeze-thaw heaving/contraction process as well as ice and snow being present in the fill material causing voids during the spring melt. In some extreme cases, deep slump holes have formed in dam walls constructed of granular material such as iron ore tailings.

Differential uplift caused by frost heave along embankment walls constructed using tills and clays has also been observed although the effect is often not as critical as settlement.

3.2 Seepage Issues

Observed seepage issues generally related to underseepage through fractured rock foundations or the seepage and associated erosion under geomembranes used in both lining and spillway application.

The underseepage was noted in areas where bedrock was highly fractured and curtain grouting measures had not been properly implemented due to either inadequate grouting design or difficult construction conditions. This had led to erosion issues at the toe of a tailings dam and was considered a significant problem as remediation is extremely difficult and costly for foundation issues.

Figure 3.1: Seepage observed at Idaho Dam at downstream toe

Seepage was also associated with the erosion problems of material supporting geomembranes on both dam walls and spillways. In one case, a geomembrane experienced horizontal tearing in excess of 100 metres due to seepage through a non-lined section eroding the supporting soil along embankment and creating a void beneath the membrane.

Case study: Raglan mine spring meltwater storage dam

The remote Raglan nickel mine is located at the extreme limit of northern Quebec and has an average annual temperature of -10 degrees Celsius. The site geology is highly fractured bedrock and has an average permafrost depth of 0.5m.

During the construction phase of the mine, a spring meltwater embankment dam was built using a frozen core supported by granular fill. Injection grouting was carried out to seal the bedrock however the grout did not penetrate adequately and seepage was noted once the reservoir was filled. The seepage through the rock foundation eventually melted the ice core, causing piping within the wall and complete failure of the dam only 2 years after its construction. The dam was replaced at large cost with a concrete core dam.

3.3 Embankment Deterioration Issues

One of the more interesting and relevant issues described by an engineer contacted as part of the study involved a process referred to as 'solifluction' in the field of periglacial geomorphology.

Solifluction is a gradual mass wasting slope process that specifically occurs in regions that experience freeze-thaw cycles. It is characterised by a slow downslope movement of water saturated earth and rocks due to recurrent freezing and thawing of the material and is driven by gravity. It is generally understood to be caused by the thawed, water laden surface layers sliding over the deeper frozen layers on a slope.

This effect was noted on the outer embankments of a few earth dams in northern regions of Canada, thought to be caused by the inadequate compaction of the outside layers. Upon investigation it was discovered that compaction rollers would often only compact properly up to 1m or more from the edge of an embankment for safety reasons, leaving a zone of material with compaction rates as low as 80-85% proctor density. This zone of lower density would become waterlogged during spring thaw and gradually slide down the embankment wall, reducing the width of material supporting the core and potentially affecting the stability of the dam.

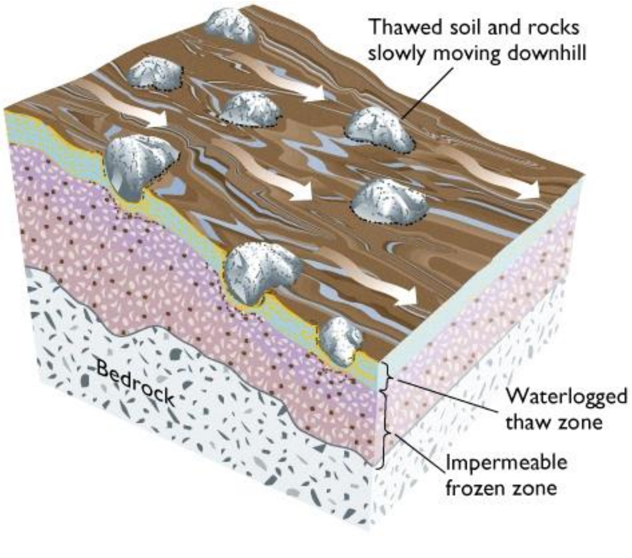


Figure 3.2: The process of solifluction (source: http://learningglaciers.blogspot.com.au)

Another more general deterioration issue encountered was the cracking and desiccation of the fine and medium grained surface layers of the embankment due to a combination of the freeze-thaw processes and evaporation from exposure to sun. The effects of this included reductions in strength and increases in permeability and dust generation.

3.4 Drawdown Related Issues

There were a number of issues experienced related to drawdown of a reservoir however the most notable in relation to cold regions was the damage to fine grained core material surrounding appurtenances and concrete outlet structures due to freezing after a drawdown. In dams with no insulation around the outlet penetration structures, drawdown below these outlets during winter led to freezing of the frost-susceptible material immediately surrounding the concrete and significant increases in permeability due to the freeze-thaw effects described in section 2.3.4. The damaged core material in these areas coupled with voids along the structure walls due to freeze-thaw expansion and contraction encouraged piping effects and led to costly repairs.

Other drawdown issues were of a stability nature, predominantly due to saturated material collapsing after the maximum drawdown rates were exceeded.

3.5 Fill Material Issues

A common issue encountered on a number of sites was the contamination of select fill material with snow and ice. When frozen material was laid and compacted, ice lenses and snow pockets subject to melting during summer months created voids within the embankment walls and core. This was mainly experienced in tailings dams where the fill material was of a coarse granular nature and the borrow areas were exposed and subject to snow fall and freezing rain. The issue was generally due to poor construction management and lack of experience.

3.6 Membrane and Geotextile Related Issues

Practical experiences showed that the application of geomembrane and geotextile systems to dams is often an efficient and viable alternative to the traditional zoned earth dam approach.

Some issues with membrane systems include:

- Difficulty of constructing with HDPE membrane in winter
- Geosynthetic Clay Liners (GCLs) difficult to install in cold climates as they need to be kept moist during installation.
- Membrane welding must be carried out to manufacturer’s specifications and checked using electro-static testing equipment before reservoir filling.
- In one case, a geomembrane experienced horizontal tearing in excess of 100 metres due to seepage through a non-lined section eroding the supporting soil along embankment and creating a void beneath the membrane.

Experience has shown that bituminous geomembrane is generally the best solution due to its temperature and weather resistance.

Figure 3.3: Bituminous geomembrane being installed on upstream face of embankment dam (source: www.coletanche.com)

3.7 Spillway Issues

Both operational and emergency spillways are integral to the success of an earth dam. The most desirable location is in natural ground or rock cut around the end of an embankment dam. In situations where this is not possible, such as ring dykes or large tailings ponds, the spillway must be built to flow over the dam wall without causing erosion or saturating the material in the embankment. In seasonally cold regions, emergency spillway design is especially critical as extremely large flows are possible within the catchment due to a combination of rapidly melting snowpack and rainfall events.

There have been a number of instances of these embankment located spillways being heavily damaged during excessive flow periods due to poor design practices such as the use of inadequately sized rock protection or poorly anchored geomembranes.

Scour of fine and medium grained material underlying rock scour protection is also a common issue which can lead to the collapse of a dam wall if left unchecked.

In one case the engineer described a situation where a geomembrane had been used as a spillway liner but erosive conditions in the material underlying the membrane had caused the support to weaken and led to a herd of caribou punching a large amount of hoof sized holes in the spillway. This had resulted in the entry of water and saturation of the remaining material, further weakening the structure.

Another issue with spillways in cold climates is the potential for blockage caused by excess snow and ice. Although no situations were referred to where this had caused any significant problems, it was identified as an area of concern.

3.8 Winter Construction Issues

Construction of embankment dams in seasonally cold climates brings a number of challenges and requires a different approach to scheduling and resource management than temperate construction projects.

The most obvious issue is the inability to construct using frost susceptible material during the winter months where soil freezing is likely to occur. This can limit construction periods to as little as 5 or 6 months of the year in some regions. Other activities such as injection curtain grouting are also very difficult and expensive to carry out in winter and must be scheduled for the warmer months. Placement of granular fill such as sand or tailings in the embankment can be continued under freezing conditions however the total depth placed should not exceed the depth that is able to thaw during summer (a rough fill limit used on some sites in northern Quebec is 3m).
During these winter periods site access may also be hindered due to deep snowpacks or icy conditions and arrangements must be made to account for this possibility.

From practical experience, it was also found that winter temperatures can have some benefit by improving the conditions on sites with soft ground, allowing machinery to access otherwise muddy or sloppy areas while the earth is frozen. Using this to advantage, many dam construction sites use the winter months to prepare and develop the site including construction of access roads, clearing of vegetation, stripping of topsoil and even key preparation.

During the interviews, one specific issue in regards to the progressive raising of earth core embankment tailings dam was raised. It had been noted that while clay and till cores are generally designed with an insulating granular layer as part of the ultimate configuration, there had been cases where tailings dams that were built in stages due to either economical or seasonal factors had not provided adequate insulation over the core during the interim construction raises, which could sometimes span over winter. This issue could potentially lead to layers of frost affected core throughout the dam and cause significant seepage and possibly piping problems over time.

Figure 3.4: Large tailings embankment dam in Fermont, Quebec

CHAPTER 4 - Recommendations

Through research of existing literature and practical experience, a number of key aspects of earth dam design in freeze-thaw climates were identified. The investigation revealed that many techniques and methods employed in the field to optimise the design and construction of embankment dams are not promoted through existing guidelines or manuals. Some of the issues identified by the engineers contacted as part of the investigation could potentially have been avoided or reduced in severity by the application of more standardised set of guidelines or recommendations than is currently available.

While the engineers interviewed were able to provide sound practical advice, results of laboratory testing and geotechnical studies offered a deeper understanding of the effects of cold climates on embankment dams. Aspects such as the macrostructural changes that soil undergoes during freeze-thaw cycles, the historical applications and success rates of alternative core materials and methods of estimating frost depth were all explored through literature reviews.

Recommendations by experienced engineers for optimising the design and construction of earth embankment dams are summarised below and relate to some of the issues described in Chapter 3.

Figure 4.1: Zoned earth embankment dam in Fermont, northern Quebec

4.1 Design Principles

4.1.1 General

1. Before any preliminary design, a feasibility analysis should be carried out which considers cost of various configurations including earth core, asphalt core and geomembrane facing. Factors which must be considered include the availability of suitable local material, hauling distance and costs of core and fill material, supply and install costs of asphalt or geomembranes, seasonal construction timeframes and cost advantages of winter construction, impact of seepage and availability of specialist equipment if needed.

4.1.2 Earth Cores

1. Earth dams should be designed to provide adequate insulation to any frost susceptible core material including clays and till (moraine). This insulating layer should be granular material with low frost susceptibility and have a thickness approximately equal to the maximum frost penetration that the site is likely to experience. If no frost depth data is available, depth can be estimated using the Modified Berggren Equation (refer section 2.2.4).
2. Cores should extend to the top of the maximum water level of the reservoir, with insulating layers built above this level. If the embankment is to be built in stages, such as a tailings impoundment dam that will be raised periodically, insulating layers are to be placed over the core at each step and removed during construction of the consecutive lift.
3. Where it might not be feasible or economical to provide a full depth insulating layer over the core, alternative measures can be implemented to guard against the deterioration of the upper regions of the core, including installation of a cutoff curtain membrane of either bituminous geomembrane or Geosynthetic Clay Liner (GCL) extending from the crest to below the potentially frost affected regions.
4. For outlet structures and other penetrations through a frost susceptible core, adequate insulation should be provided to the material surrounding the penetrating structure to prevent freezing of core material. Styrofoam is a proven and common material for this insulation.

4.1.3 Internal Drainage/Filter Systems

1. Internal drainage/filter systems should be designed to adequately reduce any pore pressures within the dam and contain the phreatic surface within the embankment. Common configurations such as the chimney or blanket filter/drain systems must be designed to consider the worst case scenario including a cracked core, hydraulic fracturing or core segregation.

2. At boundaries between materials of varying grain sizes, a filter system consisting of either a specifically graded granular material or a geotextile should be used to protect against migration of fine particles.

4.1.4 Configuration

1. Embankment dams that are likely to experience freeze-thaw cycles should be built with additional embankment width of minimum 1.0m both upstream and downstream. Once the fill material is compacted the outer layer can be stripped away, leaving only the material which was compacted to optimum density by the rolling equipment. This technique will help to alleviate problems such as solifluction (see section 3.3).

4.1.5 Membrane Systems

1. When considering membrane facing as a suitable alternative to earth core, preference should be given to bituminous geomembrane due to the proven tolerance to extreme temperature variations, sunlight and strength when compared to other types such as PE plastic membrane systems.
2. Geomembranes should be installed in vertical strips on the upstream face of the embankment to avoid horizontal seams. The bedding material should be of a grain size that will not puncture or tear the membrane under vehicular loading. Sufficient protective cover should be provided over the top of the membrane, with a recommended minimum cover thickness 0.5m.

4.1.6 Spillways

1. Where a spillway is required to be located in part of the embankment, a bituminous geomembrane anchored at the upstream toe of the embankment and extending over the crest and down the downstream slope is recommended to be used to prevent scour. The membrane should extend along the embankment far enough on each side of the spillway to prevent water migration under the membrane.
2. Rock protection underlain by geotextile should be used for outlet and drainage channel lining downstream of the spillway. Rock sizes should be large enough to maintain stability under full flow conditions. An approximate diameter for rock protection is 0.6m diameter dumped rock.

4.2 Material Selection

1. Even if local clay or till is available for core material, careful consideration should be given to alternatives such as asphalt concrete cores or bituminous geomembrane facing which could cut construction costs and reduce potential problems in the long term.
2. An approximate guide for filter material selection is based on the filter being roughly 100 times more permeable than the surrounding fill to successfully draw the water away (refer section 2.2.3)
3. Core material should contain a sufficient amount of fines to meet permeability requirements. Locally sourced clay and till (moraine) is a proven and cost effective core material, however a grain size analysis should be performed before the material is adopted.

4.3 Construction Methods

1. The compaction of filters and drains should be limited to about 70 percent relative density, to avoid particle breakdown and increased permeability.
2. Contamination of the filters during construction should be minimized by restricting the crossing of filter zones with construction equipment to specific locations protected by geomembranes or protective fill.
3. Insulating blankets and tarps should be used to keep lifts from freezing during placement and compaction of the dam.
4. The exposed face of the borrow pit should be minimised to prevent any significant freezing of the borrow material during construction.
5. Fill material should be free of frost, snow and ice when placed to prevent ice lensing and possible sinkholes. No material should be placed on already frozen material in the embankment dam or ground.
6. Injection grouting should be avoided during winter, however if necessary ground heating methods can be implemented to thaw ground before injection. Grouting should be thoroughly pressure tested with water pumps before the dam is constructed on top to prevent expensive repairs.
7. Lifts should be laid in layers that allow compaction to achieve a minimum density of 95% proctor at optimum moisture content. A good starting point is lifts of 0.3m, however compaction testing should be carried out once construction commences and lift thickness adjusted if adequate compaction is not being achieved. Additional thickness provided to the embankment walls (refer section 4.1.4) should be scraped away from the outside once the dam is fully constructed.
8. Engineers should be in close contact with contractors during the construction phase, checking compaction, seepage rates and material quality. If any adverse issues are experienced, they should be ready to adapt the design or look at suitable alternatives.

CHAPTER 5 - Conclusions and Future Work

During the process of researching, collaborating and interviewing for this dissertation it was clear that the objective defined for the project was relevant and had some potential to progress beyond the conclusion of this paper. The need for clear and specific guidelines and recommendations for the design and construction of embankment dams in seasonally cold regions was identified as an area of where further input would be valuable to the engineering sphere. It was however recognised that the development of technical guidelines for use by the wider engineering community is a controlled and rigorous process and can only be carried out with the cooperation of a committee and the content agreed upon by consensus. This project aimed to provide a platform of ideas and recommendations to encourage the development of these guidelines by associations such as the Canadian Dam Commission (CDA) or the International Commission on Large Dams (ICOLD).

The recommendations presented in Chapter 4 represent a fusion of theoretical and laboratory based knowledge with practical field tested methods. The methodology involved with the project preparation included contact with active professionals working in the field of cold region embankment dam design in order to connect the literature studies with the real world. The focal areas of Design Principles, Material Selection and Construction Methods were developed to provide clear direction and relevant recommendations for engineers involved in the feasibility, preliminary and detail design and construction stages. The intention was for the recommendations to be used as a technical reference in conjunction with other more in-depth general embankment design manuals and guides currently available, rather than a standalone complete dam design manual for cold regions.

It was a conscious decision not to explore other associated areas such as dam siting, social and environmental issues, hydrological and seismic aspects and monitoring methods. These aspects are all integral to the design process however the scope of this project was kept concise to allow the development of well researched findings in some key areas rather than attempt to cover too many bases.

Further Work

The next step is to pass a copy of the completed paper onto a committee chairman of the Canadian Dam Association that has helped me with the project who may also be able to present the findings to ICOLD for consideration for a technical bulletin. If an interest is expressed by either the CDA or ICOLD, I intend to remain in contact and possibly be involved with further work and refinement.

During the process of preparing this dissertation I have increased my already strong enthusiasm for earth and tailings dam design, especially advancing my knowledge of applications to cold climate construction. I hope to continue this learning path into my career, with plans to work in countries where this can be applied, such as Canada.

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Appendix A

Project Specification

University of Southern Queensland

FACULTY OF ENGINEERING AND SURVEYING

ENG8411/8412 Research Project

PROJECT SPECIFICATION

FOR:	JAMES BLYTH
TOPIC:	OPTIMISING EARTH DAM DESIGN IN SEASONAL FREEZE-THAW CLIMATES
SUPERVISOR:	(not allocated yet)
PROJECT AIM:	To develop a suitable set of guidelines for best practice design of earth dams in seasonally cold climates, focusing on material behaviour and characteristics under repeated freeze-thaw cycles.
PROGRAMME:	**(Issue A, 12 March 2013)**

1. Research scientific papers, engineering journal articles and existing design guidelines from around the world on earth dam design specifically relating to application in freeze-thaw climates.
2. Conduct interviews and correspond with a number of highly experienced geotechnical engineers that have designed and built large earth dams in northern parts of Canada and the USA to establish some tried-and-tested methodologies and practices for earth dam construction.
3. Critically evaluate current published design methodology for earth dams in seasonally cold climates.
4. Consolidate all relevant findings into a framework of guidelines for optimising earth dam design in seasonal freeze-thaw climates.
5. Submit an academic dissertation on the research.

- *As time permits:*

6. Using the USQ engineering facilities and testing equipment, carry out bearing capacity and permeability testing of various materials before and after undergoing a pattern of freeze-thaw cycles.
7. Investigate the various types of geotextile and membranes that are used in dam construction and possibly carry out freeze-thaw tests on some samples.

AGREED ___________________ (Student) _________________________________
(Supervisor/s)

____ / ____ / 2013 ____ / ____ / 2013

Examiner/Co-examiner: ____