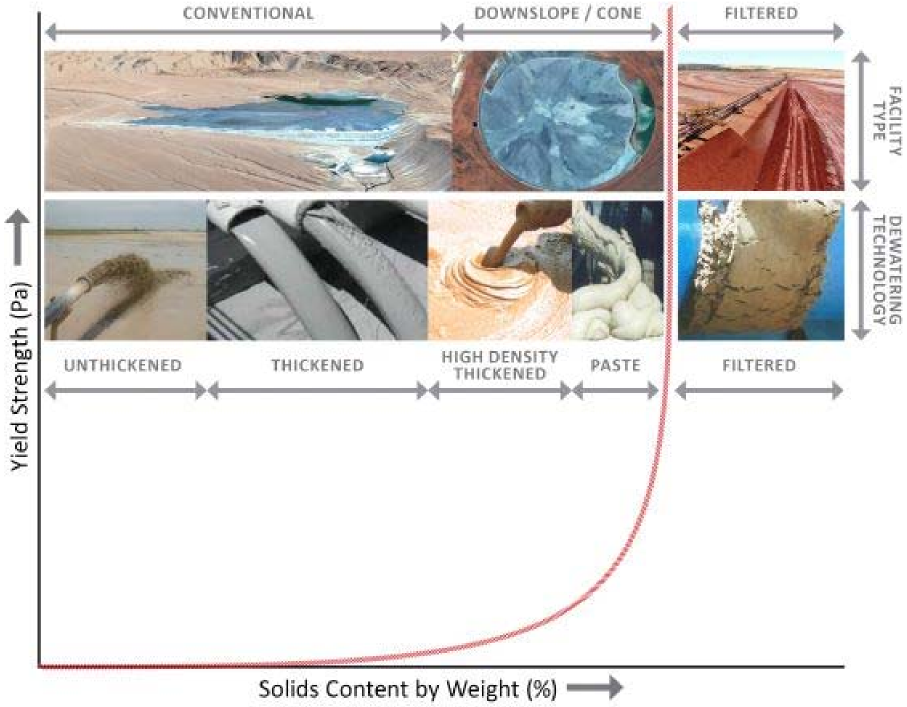
TAILINGS DAM DESIGN
Technology Update



Klohn Crippen Berger (2017) & Google Earth (2019)

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(2013-2019)

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GLOSSARY

Abbreviations

ABA	Acid Base Accounting
AMD	Acid Metalliferous Drainage (see also Acid Rock Drainage)
ARD	Acid Rock Drainage
ART	Altered Rock Tailings
ASTM	American Society for Testing Materials
CPT	Cone Penetration Testing
CT	Coarse Tailings
EN	European Standard
EU	European Union
FT	Fine Tailings
ICARD	International Conferences on Acid Rock Drainage
ICOLD	International Commission of Large Dams
INAP	International Network for Acid Prevention
W_L	Liquid Limit
I_L	Liquidity Index
MEND	Mine Environment Neutral Drainage
ML	Metal Leaching
NAG	Non-Acid Generating, see also Non-Acid Forming (NAF)
NAGpH	Net Acid Generation pH
NAPP	Net Acid Producing Potential

NMD	Neutral Mine Drainage
NPR	Net Potential Ratio
NRD	Neutral Rock Drainage
PI	Plasticity Index
PAG	Potentially Acid Generating see also Potential Acid Forming (PAF)
PAF	Potentially Acid Forming
SD	Saline Drainage
SL	Shrinkage Limit
C_u/σ'_{vo}	Peak Undrained Shear Strength Ratio
C_{ur}/σ'_{vo}	Residual or Large Strain Undrained Shear Strength Ratio
TMF	Tailings Management Facility see also Tailings Storage Facility (TSF)
TSF	Tailings Storage Facility
UFT	Ultra-Fine Tailings

DEFINITIONS

Tailings dam (also Tailings Management Facility (TMF) and Tailings Storage Facility (TSF)): an engineered structure, comprising the confining embankment and associated works, designed to contain tailings resulting from ore processing and to manage associated water.

Confining embankment: an engineered dam that can be constructed from both natural and processed geotechnical materials, designed to retain the tailings and process water derived from the mineral-processing plant, and natural runoff.

Decant: an engineered structure designed to facilitate removing of process water and storm water runoff from the tailing impoundment.

Emergency spillway: an engineered structure designed to pass the design flood event without endangering the stability of the confining dam.

Solids concentration: the percent solids by weight of a tailings water mixture.

Closure: the stage of the tailings facility after operations have ceased. Closure stages range from decommissioning to active closure, passive closure and facility relinquishment.

SUMMARY

Tailings are produced from the processing of mineral ores and are commonly stored within embankment dams. The design of the dams requires application of sound engineering principles and an understanding of the properties of the tailings. This Bulletin provides a framework for classifying different types of tailings, ranging from ultra-fine to coarse, based on their geotechnical properties and provides typical geotechnical parameters for the different tailings types. An understanding of the strength of tailings continues to improve with new technologies, e.g. cone penetration testing, and improved sampling and laboratory techniques, and case histories from dam incidents and failures improves our knowledge of tailings behaviour. The in situ behaviour of tailings is controlled by the types of tailings and dewatering and disposal techniques.

Technologies for dewatering tailings to reduce the risk of storage continue to be developed and the different technologies, from thickening to filtration, and re-application of old technologies are presented to illustrate the options available and, where appropriate, typical in situ properties.

This bulletin is directed towards a wide audience of stakeholders: designers, owners, regulators, communities and various organizations and provides a reference for communicating tailings properties and the benefits and limitations of technologies.

All mining operations, and thereby tailings operations, are unique. There is no one-solution-fits-all. Tailings dam designs need to account for site-specific conditions, such as climate, physiography, geochemistry, geomorphology, seismology, mining processes, environment and community setting, with the application of technologies playing an important role in developing safe, sustainable tailings facilities.

FOREWARD

The previous bulletin relating to tailings dam design prepared by the ICOLD Tailings Dam Committee was ICOLD Bulletin No. 106, Guide to Tailings Dams and Impoundments, which was published in 1996. Since that time there has been an improved understanding and application of new technologies and experiences gained from assessment of hundreds of tailings facilities for a wide variety of ores and varying physiographic, climatic, and geochemical conditions.

One objective of this bulletin is to share the knowledge gained, both on tailings properties and disposal technologies, and to put into perspective the challenges associated with “new” technologies. Design of tailings dams, as always, requires application of sound geotechnical principles, which continue to mature with ongoing research and development. Reducing risk through design and application of technologies is the objective of the tailings practitioners and stakeholders.

The ICOLD Working Group members provided valuable time and technical input into this bulletin and deserve special thanks. The member countries also provided valuable input during our Committee meetings and with review of this document. We also wish to thank reviewers from the National Committees and from industry experts.

HARVEY MCLEOD
CHAIRMAN
COMMITTEE ON TAILINGS DAMS AND WASTE LAGOONS

PREFACE

Tailings dams are unique engineering structures in that they are often constructed over a long period of time and the materials used for the dam can include processed or unprocessed tailings or natural borrow material or mine rock. While new technologies, such as filtered tailings, can produce a material that can be compacted, there are challenges with considerations of climate physiography and geochemistry. The wide variety of types of tailings, from ultra-fine to coarse, requires an understanding of their properties to optimize the design and to reduce physical and environmental risks.

The state of practice for understanding the strength parameters of loose tailings deposits continues to evolve and the framework of critical state soil mechanics is a useful tool for understanding contractant (loose) and dilatant (dense) behavior.

Dewatering technologies continue to improve with larger plants and reduced costs and the creation of tailings landforms for safe sustainable closure are the objectives of good design.

Guidelines for safe design of tailings dams and waste lagoons is a key focus of the Tailings Subcommittee and recent ICOLD publications include:

- No. 106A 1996 A Guide to Tailings Dams and Impoundments
- No. 121 2001 Risks of Dangerous Occurrences
- No. 139 2011 Improving Tailings Dam Safety
- No. 153 2013 Sustainable Design

1. INTRODUCTION

Mining and industrial processing are major international industries which may produce large volumes of fine-grained waste material known as tailings. Tailings are the by-product that remain after processing. Processing can include:

- crushing, grinding and processing ore to recover minerals;
- beneficiation processes that upgrade ore, coal or mineral ores by removing unwanted materials;
- washing processes including sand or coal washing and clay upgrade;
- residues derived from: ash and slag from combustion of coal, or from blast furnaces, bauxite refining, processing laterite nickel, etc.; and
- by-products from chemical reactions within a process (e.g., gypsum).

This Bulletin updates the evolving understanding of tailings properties and technologies related to their dewatering and disposal, along with the associated dams and containment structures. Its focus is the technical design of the confining dams. Management related aspects, which are equally important, are not specifically addressed.

This Bulletin is directed towards a wide audience of stakeholders: designers, owners, regulators, communities, and various organizations. It is meant as a reference to improve knowledge on tailings properties and developments and trends in design of tailings dams. While it is not a prescriptive design guide document, it is intended to bring attention to new technologies, updates to old technologies, as well as describe their key benefits and deficiencies with the objective of improving the practice of tailings dam management.

Safe tailings management is a critical component of mine risk management, as illustrated with recent significant tailings dam failures and the potential for high environmental, social and economic impacts. The management of tailings is, therefore, crucial, and many books, technical papers and other commentaries, have been published on the topic. The principles of sound engineering for tailings dams are commonly available but need to be applied throughout the tailings life cycle, from early construction to decommissioning and final closure.

All mining operations, and thereby tailings operations, are unique. There is no one-solution-fits-all. Tailings dam designs need to account for site-specific conditions, such as climate, physiography, geochemistry, geomorphology, seismology, mining processes, environment and community setting, with the application of technologies playing an important role in developing safe, sustainable tailings facilities. Some design drivers include:

- increased production rates and increased tailings volumes as mines get larger;
- remote mines, together with very challenging environments; requirements to minimize water and energy consumption,
- requirements to reduce land disturbance;
- requirements to minimize the impact on air (dust), and surface and ground waters; and,
- increased focus on community safety, and minimization of potential risks to communities, resulting from tailings dam failures.

New technologies emerge, and old technologies are improved to satisfy the design drivers. For example, significant effort has been put into advancing the tailing dewatering (filtration) technologies with a goal of improving safety and water recovery.

The ICOLD committee on Tailings Dams and Waste Lagoons has, since 1989, produced 12 Bulletins on different aspects of tailings dams, with the objective of increasing their safety. The focus of the last two Bulletins (no. 139 and 153) has been on safe design for operation and closure. This Bulletin is complementary to these previous Bulletins and focuses on understanding the different types of tailings and improvements in design of tailings dams over recent years. It is based on the experience of committee member — tailings dam specialists from over 15 different countries.

One of the messages of this Bulletin is that each technology can be successfully applied under appropriate conditions, but not all technologies can be used for all conditions. The application of each technology must be carefully evaluated by an experienced designer and carried out by an experienced operator. The reader is cautioned that the design of tailings dams is complex, and it is essential that qualified engineers advance the design and construction of tailings dams with due consideration of the issues discussed in the subsequent technical sections of this bulletin.

The main sections of the Bulletin are:

- Tailings properties – describes the geotechnical and geochemical characteristics of the tailings, not only as determined during the laboratory testing stages, but also which properties change during construction, operation and closure.
- Tailings technologies – describes the recent developments in tailings processing, tailings transport systems, and tailings deposition strategies.
- Tailings dam design practices – describes the developments in tailings dam engineering and containment strategies and their application to increasing trends to consider complex cross sections, dam safety and environmental containment.

2. TAILINGS PROPERTIES

2.1. INTRODUCTION

The geotechnical properties of the tailings affect the performance of the dam during both operation and post closure. Material characterisation forms a fundamental part of the design, as well as being essential during operation to ensure that the assumed parameters for the dam and the containing structures are achieved. Material characterisation for geotechnical purposes involves identifying the range of properties of the tailings. However, at its basic level, tailings classification involves the arrangement of tailings into groups that have similar properties and characteristics.

In addition to identification of basic mineralogical constituents, material characterisation for geochemical purposes involves assessing the potential for deleterious changes in material properties resulting from chemical alteration, particularly the acid generation potential. Such characterisation also includes the identification of any hazardous/dangerous substances, and the potential for their release in to the environment. Due to the common constituents of ore bodies and their potentially elevated sulphide content, acid generation is important for geochemical characterisation. There are several acid generation classification systems available globally, for which expertise is required in determining the most appropriate method for each jurisdiction. In addition, neutral metal leaching and salinity and sulphate, cyanide, thiosalts and other deleterious elements influence the environmental setting/management of the TSF. To this end, non-standard geochemical tests may be required to understand the geochemical behavior of the tailings.

The purpose of this section is to describe the different types of tailings and their geotechnical and geochemical properties. The section includes the quantification of the main factors controlling the tailings properties, provides examples of properties for typical types of tailings, and includes discussions on how these properties may impact the selection of the TSF and confining dam design. It is noted that the long-term geotechnical and geochemical stability, as well as disposal efficiency, is founded on the fundamental knowledge of the tailings properties.

2.2. CLASSIFICATION OF TAILINGS

Tailings typically have similar properties to natural unconsolidated soils, however, the processing, transportation, deposition and the geochemical characteristics may impart non-standard properties to the tailings both at particulate and mass deposition level. Tailings properties differ, however, depending on the orebody, mineralogy and the processing and/or degree of grinding. For example, high clay contents or the presence, sometimes in relatively small quantities, of montmorillonite clays, significantly influence the consolidation and engineering properties. Other examples include pyrophyllites and complex precipitates from metallurgical processes. Table 2.1 presents a summary of tailings types classified into 5 different categories. The classification system is like those presented by Fell et al. (2005) and Vick (1990), however, the categories have been structured to include the continuum from coarse tailings through to ultra-fine clay tailings.

Table 2.1
Summary of tailings types and geotechnical classification

Tailings Type	Symbol	Description (compare)	Example of mineral/ore
Coarse tailings	**CT**	Silty SAND, non-plastic	Salt, mineral sands, coarse coal rejects, iron ore sands
Hard Rock tailings	**HRT**	Sandy SILT, non to low plasticity	Copper, massive sulphide, nickel, gold
Altered Rock tailings	**ART**	Sandy SILT, trace of clay, low plasticity, bentonitic clay content	Porphyry copper with hydrothermal alteration, oxidized rock, bauxite. leaching processes
Fine tailings	**FT**	SILT, with trace to some clay, low to moderate plasticity	Iron ore fines, bauxite (red mud), fine coal rejects, leaching processes, metamorphosed/weathered polymetallic ores
Ultra Fine tailings	**UFT**	Silty CLAY, high plasticity, very low density and hydraulic conductivity	Oil sands (fluid fine tailings), phosphate fines; some kimberlite and coal fines

Note that this table excludes the ultra-coarse tailings derived from dense media separation (DMS) circuits, which generally comprise uniformly graded medium to fine gravel sized particles.

The five tailings types are summarized as follows:

- Coarse tailings – generally a cohesionless angular soil exhibiting medium–high shear strengths and high hydraulic conductivity. However, in the case of salt tailings, solubility and localised solution effects may reduce hydraulic conductivity and impart a degree of apparent cohesion. In the case of coarse coal tailings, the properties will be heavily dependent on the sedimentary sequence from which the material is derived. For instance, brittle and flakey elements may exhibit lower shear strength and hydraulic conductivity when loaded.

- Hard rock tailings – particularly those derived from igneous and metasedimentary rocks generally exhibit angularity, good shear strength, and a hydraulic conductivity directly related to the grading, i.e., conforming to the Hazen (1982) relationship. However, on comminution, some metamorphic rocks produce a finer fraction, which may exhibit different properties from the main constituents of the tailings. These finer fragments may dictate the properties of the tailings deposit or impact the deposition process, which may make them behave as altered rock tailings. The fine portion of segregated hard rock tailings may also behave more as altered rock tailings.
- Altered Rock tailings – derived from rocks that have undergone some alteration of the feldspar minerals to clay minerals, or with naturally occurring clay minerals. These tailings exhibit moderate settling characteristics and shear strength dependent on the quantity and type of clay fraction. However, if there is >5% -2μm fraction, the tailings may exhibit similar properties to fine tailings.
- Fine tailings – generally a silt-dominated product, often containing clay size fractions. Where fine particles result from the comminution process, the fines may comprise “rock flour” and thus will not exhibit clay-like characteristics.
- Ultra-Fine tailings – a particulate product whose properties are defined by the finest (clay) fraction and may comprise natural clays, decomposition products, or tailings derived from acid neutralisation processes such as bio-oxidation or water treatment sludges. Ultra-fine tailings are characterised by low hydraulic conductivity and density. Without intensive drainage, or exposure to evaporation in arid climates, ultra-fine tailings may take hundreds of years to consolidate.

As is evident from Table 2.1 there is a broad range of tailings whose primary properties are dependent on the geology of the originating deposit, as well as the ore types and range, from metal ores through bauxite and coal to industrial minerals. The primary ore related properties are altered by the different processing methods, such as gravity concentration, froth flotation, electrostatic separation, magnetic separation, leaching and oxidation. Most processes involve a degree of crushing and grinding in the comminution circuit, which influences the geotechnical characteristics of the tailings. These are further affected by the downstream physical processes, such as dense media separation, thickening, pH adjustment, sulphide removal and separation of fine and sand size fractions. Additionally, segregation during deposition changes the gradation, and hence tailings classification, of the coarser and finer fractions.

2.3. TAILINGS PROPERTIES – LABORATORY-BASED

2.3.1. Introduction

The determination of tailings properties (parameters) must consider not only those properties associated with the nature of the particulates, but also their in situ state and the overall structure of the tailings mass, as follows:

- the geotechnical nature of the tailings is defined by the particle size distribution and the percentage and plasticity of the clay fraction.
- the in situ state is determined by the density, water content, stiffness and strength.
- the structure of the tailings mass is defined by the interlayering and segregation that occurs during deposition, of which features would be removed by sample reconstitution.

Laboratory-based tests are, under most circumstances, only able to determine those properties associated with the in situ state of the tailings samples collected, which are then extrapolated to field conditions. The properties of the tailings mass can only be determined by obtaining high quality, undisturbed samples from the field or from in situ testing using cone penetration testing (CPT). In addition, and of paramount importance for tailings derived from sulphidic ores, is the need to understand and quantify the impact on the deposited tailings if oxidation and geochemical alteration occurs during deposition. All laboratory-based test work must, in addition to considering the physical properties of the tailings, assess how these properties may be affected by geochemical influences.

The design of the laboratory testing program for tailings needs to consider the proposed milling process, the potential tailings deposition plan and the potential geochemical properties. Tailings samples are usually generated at the design stage of the project with the use of "lock – cycle" tests, which simulate the proposed process. However, at this stage of the project, the process flow sheet design may be fluid, the samples available for testing limited in volume, and available material may not be fully representative of the ore body. The property data derived from tailings samples provided at the design stage should, therefore, be treated as indicative only with ongoing tailings characterisation testing planned for both design confirmation and construction quality assurance purposes. Reference should be made to tailings case histories and literature with similar types of tailings. Further, the characterisation of geotechnical properties should be an ongoing requirement to reflect actual conditions during the mine life.

Thickening of tailings increases the solids concentration. For example, hard rock tailings with a specific gravity of 2.75 can achieve up to 50% in conventional thickeners, and up to 65% and occasionally 70%, with high density or high rate thickeners Further discussion on thickening is presented in Section 3.4 of this Bulletin. Further dewatering of tailings requires the use of filtration technologies, which can increase the solids concentration to near its optimum moisture content for compaction.

The representativeness of the tailings samples needs to be integrated with the mining and milling plan to confirm that the tailings are representative of the mineralogy, particularly of the clay fractions of the ore deposit. It is not unusual for tailings produced from complex, altered ore deposits to have a range of material properties and, hence, tailings types which, on some mine sites, is directly related to different geological units within the ore bodies.

Other considerations in the design of the laboratory testing program include: sedimentation, evaporation and drainage conditions, geochemistry and testing for potential use such as dam embankment construction, e.g., cyclone tailings.

Design parameters derived from geotechnical testing are important in confirming the size and configuration of the TSF, the rate of rise of the main confining embankment, the required sequential construction intervals, the embankment stability, and closure plan. Geotechnical testing results are also used in assessing the need for basin and embankment drainage systems, as well as designing tailings transportation systems and defining depositional methodology.

The various tailings streams should be subjected to a series of characterisation, sedimentation, desiccation, and strength tests, as appropriate, to evaluate their performance under deposition scenarios and solids concentrations. This could be significant, particularly where there could be environmental or structural benefits from dealing separately with the individual streams, such as in different parts of a TSF or in separate TSFs. Ongoing developments in mineral processing continue to open the opportunities for segregating “neutral” tailings from more hazardous tailings, which can be managed separately.

2.3.2. Index Properties and Gradation

Index properties are used for basic characterization of the tailings and are the intrinsic properties of the material which might be expected to remain constant over time. Index properties typically include:

- Specific gravity
- Particle size distribution (gradation)
- Atterberg Limits, Liquidity Index and Shrinkage Limit

Specific gravity directly affects the density of the tailings. Typical values of specific gravity for various tailings types are summarized in Table 2.2.

Table 2.2
Typical specific gravity of types of tailings

Examples of Tailings Source	Tailings Type	Specific Gravity (t/m^3)
Salt	CT	1.5
Iron ore sands or coarse coal rejects	CT	2.5 – 2.8
Gold, copper	HRT - ART	2.7
Sulphidic ores	HRT - ART	3.2 – 3.8
Base metals	HRT - ART	3.5 - 4.2
Bauxite	FT	2.7 – 3.0
Coal fines (varies with percentage of coal)	FT	1.6 to 2.2
Mine water treatment residues	UFT	<0.3
Leach residues/ Bioxidation fine tailings	UFT	< 1.0

Tailings gradation is influenced by (a) the ore genesis, (b) the degree of grinding in the comminution circuit, (c) the alteration products and clay the fractions present in the orebody, (d) the degree of washing or sorting and, at some mine sites, (e) the final stages of extraction (flotation, leaching, oxidation, etc.). Figure 2.1 presents the typical range of gradation for the various tailings classifications described in Table 2.1. The indicative gradation curves assist in understanding the basic properties of the tailings, with respect to behaving as a sand, silt or clay.

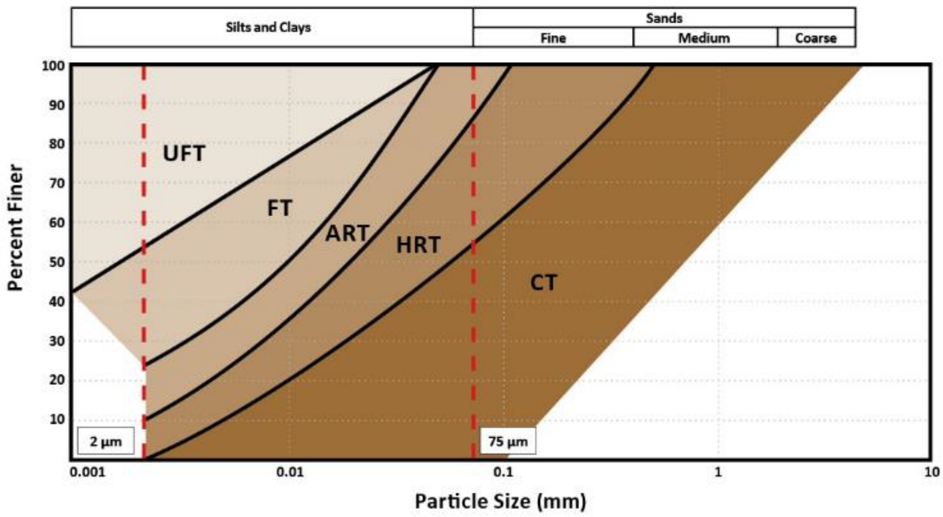


Fig. 2.1
Typical gradation range for tailings types

The plasticity of the tailings is controlled by the clay fraction and the types of clays present in the tailings. High plasticity tailings are characterized by poor settling and consolidation parameters, low shear strength, and low hydraulic conductivity. Figure 2.2 presents an Atterberg Limits chart indicating typical limits for the various tailings classifications.

It is noted that some tailings with an elevated percentage of -2μm particles may exhibit low plasticity due to the angularity of the finest fraction, which represents rock flour rather than a true clay fraction.

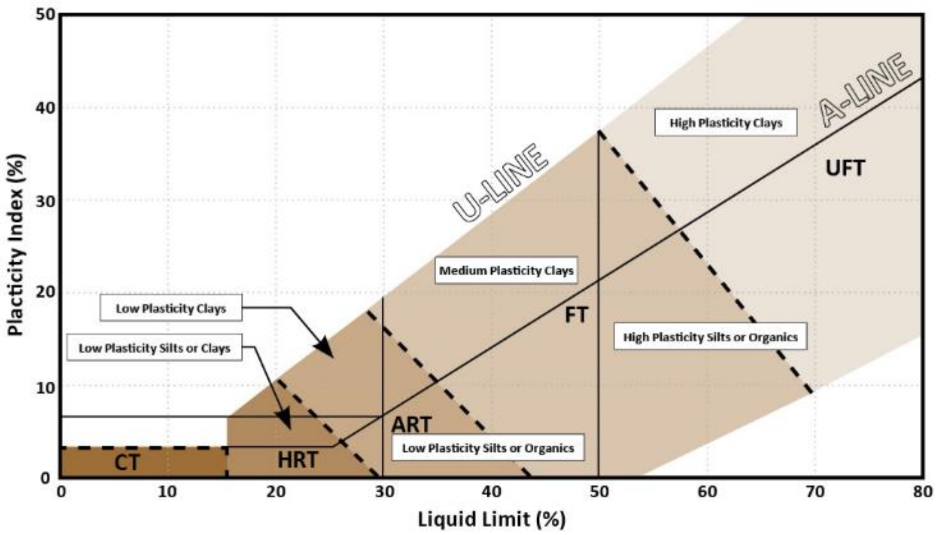


Fig. 2.2
Plasticity chart for tailings types

The activity index of the clay fraction (plasticity index / % clay (< 2μm)) provides an insight into the type of clay and can be used, along with X-ray diffraction and mineralogical analysis, to further characterize the fine fraction and the presence of other minerals. The clay fraction, particularly the dominant mineral type, can impact the consolidation properties for the tailings and the constructability for embankment fill, as summarized in Table 2.3. The activity index of the clay also provides an indication of the swelling potential of expansive clays. Clay with an activity index <0.75 is considered inactive, while clay with an activity index >1.25 is considered active and has swelling potential.

Table 2.3
Summary of clay source influence on hydraulic conductivity, settling properties and moisture sensitivity

Clay Type	Plasticity	Activity Index	Hydraulic conductivity Influence	Settling Characteristics	Constructability Moisture Sensitivity
Rock flour	Non-plastic		Hydraulic conductivity directly related to Hazen values	Generally good settling properties	Moisture sensitive during construction
Kaolinite	Low plasticity	0.40	Upper end of clay hydraulic conductivity	Generally good settling properties	Sensitive to moisture content during construction and exhibits moderate consolidation rates
Illite	Medium plasticity	0.90	Intermediate hydraulic conductivity between kaolinite and montmorillonite	Intermediate between kaolinite and montmorillonite	Intermediate between kaolinite and montmorillonite
Montmorillonite	High plasticity	>1.5	Very low permeabilities	Poor settling properties with light weight flocs easily disturbed by wind and wave. Slow rate of consolidation	Sensitive to moisture content during construction and exhibits high settlements and slow consolidation rates

Figure 2.3 shows an Activity Chart which relates the plasticity index and the clay fraction for the tailings types and illustrates the typically associated clay types. The Activity index is important in understanding the hydraulic conductivity/consolidation characteristics of the tailings and thus its in situ density. There is a direct relationship between clay mineralogy and settlement characteristics—the higher the activity, the more problematic sedimentation and consolidation becomes.

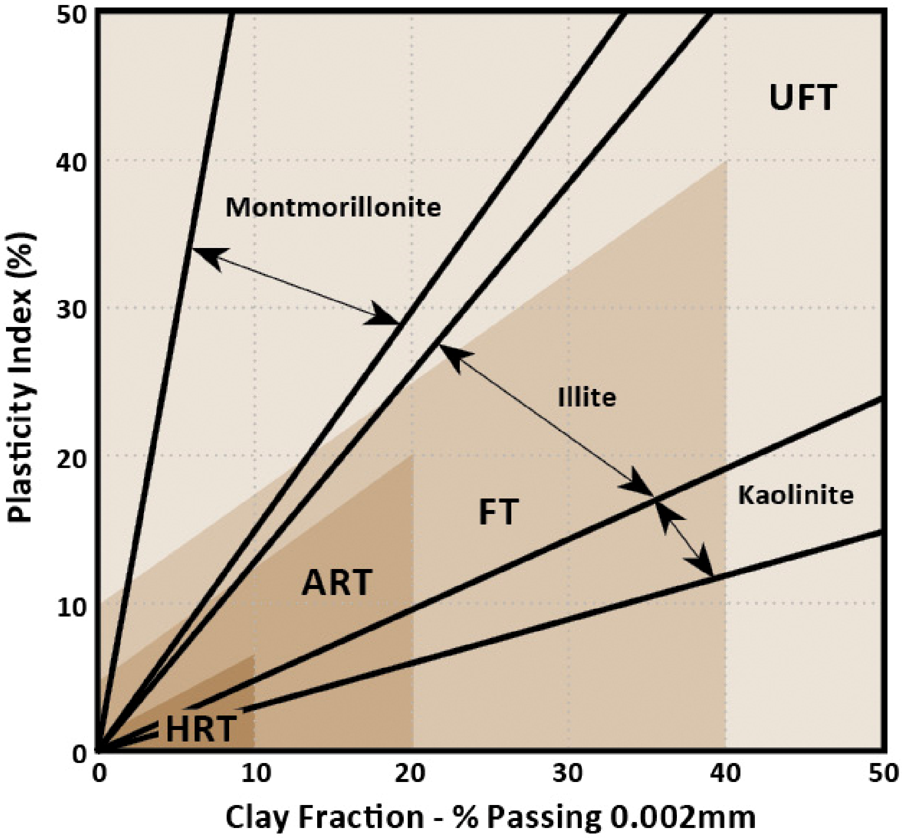


Fig. 2.3
Range of plasticity index and clay fraction (Activity) for different clay types and tailings types

Shrinkage Limit and Liquidity Index

The shrinkage limit (w_L) is the moisture content at which no more volume change occurs on drying. The w_L can be used in conjunction with drying tests to understand the behaviour of tailings as they dry, and the potential of desiccation cracks forming.

The liquidity index (I_L) is equal to: (water content – plastic limit)/plasticity index. Where I_L is >1, remoulding can transform the tailings into a thick viscous slurry. Understanding the variation of I_L in the in situ state of tailings can inform behaviour of the tailings under static or dynamic loading. This is also an important consideration in the static liquefaction of tailings and the potential consequences of a dam breach runout of tailings.

2.3.3. Settling, Consolidation and Density Properties

The settling of tailings can be complex and combines the processes of particle sedimentation, flocculation, segregation, and consolidation. Sedimentation influences the efficiency of deposition and the clarity of the settled supernatant water for recycling. Consolidation transforms the tailings from a slurry-like material to a soil-like material. Sedimentation and consolidation can also, in some cases, be affected by the characteristics of the process water (for example, where active clays are present with saline process water). This section describes different types of testing used to characterize the settling and consolidation properties.

Relationships Between: Solids Concentration, Void Ratio, Density, Specific Gravity and Moisture Content

The settling and consolidation tests can be correlated to the solids concentration of the tailings slurry, specific gravity, dry density, void ratio and moisture content of the settled solids, as shown on Figure 2.4, Figure 2.5 and Figure 2.6.

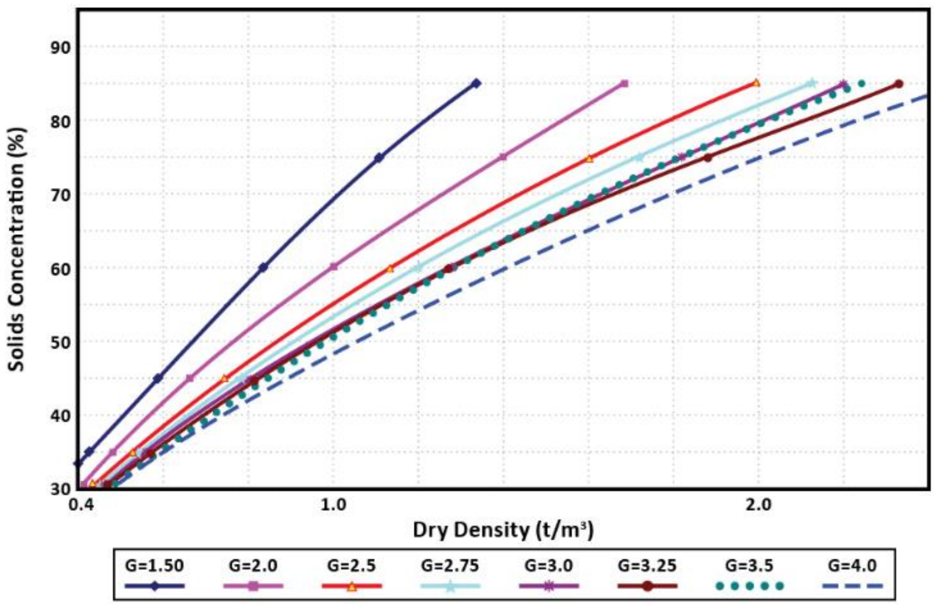


Fig. 2.4
Solids concentration (%) versus dry density for different specific gravities (G)

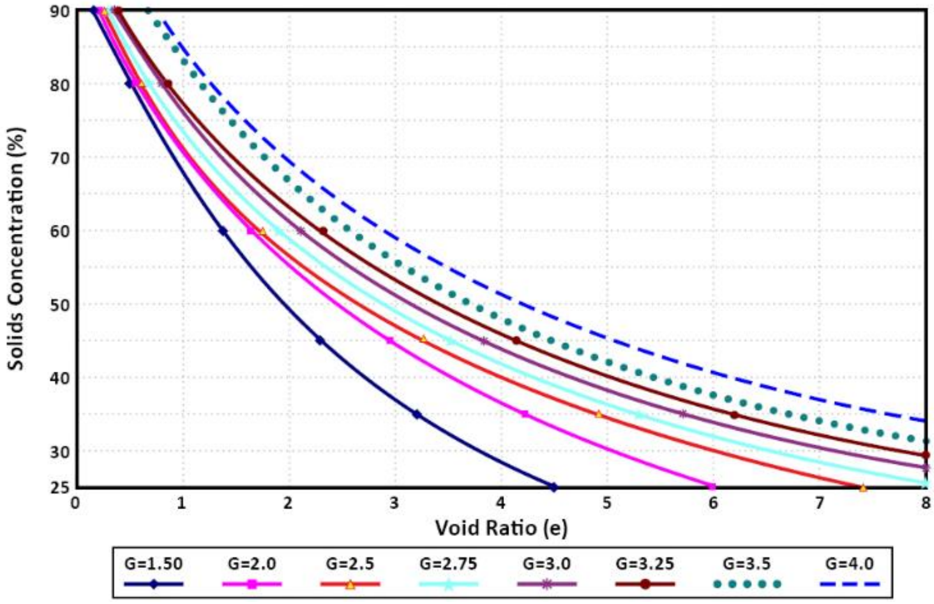


Fig. 2.5
Solids concentration (%) versus void ratio for different specific gravities (G)

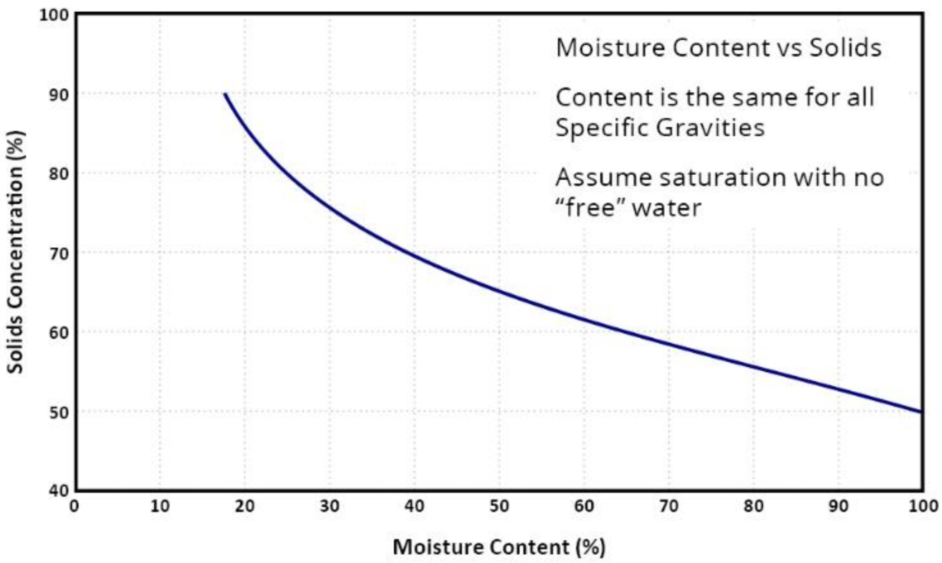


Fig. 2.6
Solids concentration (%) versus moisture content (%) for saturated tailings

2.3.3.1. Settling test

For hydraulically deposited tailings, initial sedimentation occurs as the solid particles settle and form point-to-point contact under very low stresses. The initial water release associated with the sedimentation forms most of the reclaimable water in a TSF. Subsequent tailings consolidation and water release continue thereafter at a slow rate under the principles of conventional, effective stress soil mechanics. During this initial sedimentation, the tailings solids settle and typically leave a clear interface between the top of the settling mass and the supernatant liquid. This process can be simulated in the laboratory with “jar settling tests”. This test can utilize a two-litre glass beaker approximately 12.5 cm in diameter and 16 cm in height, to minimize effects of side wall friction. Elder (1985) observed that the settlement rate was not influenced by a column diameter of 10 cm or larger. Consequently, the standard use of a hydrometer cylinder for settling tests should be carefully considered and, if used, should be calibrated with the larger beaker. The settling tests are typically run for up to five days and, depending on the % clay present, clear water may develop within hours (or in some cases it will not develop). It is also important to undertake the tests using process water rather than deionised or tap water, particularly in relation to significant differences in pH or salinity.

The settling test is influenced by the solids concentration of the tailings slurry and, in general, a higher initial solids concentration results in a slightly higher settled density. Figure 2.7 shows indicative results of settling tests for the various tailings types listed in Table 2.2. An indicative void ratio is provided for comparison.

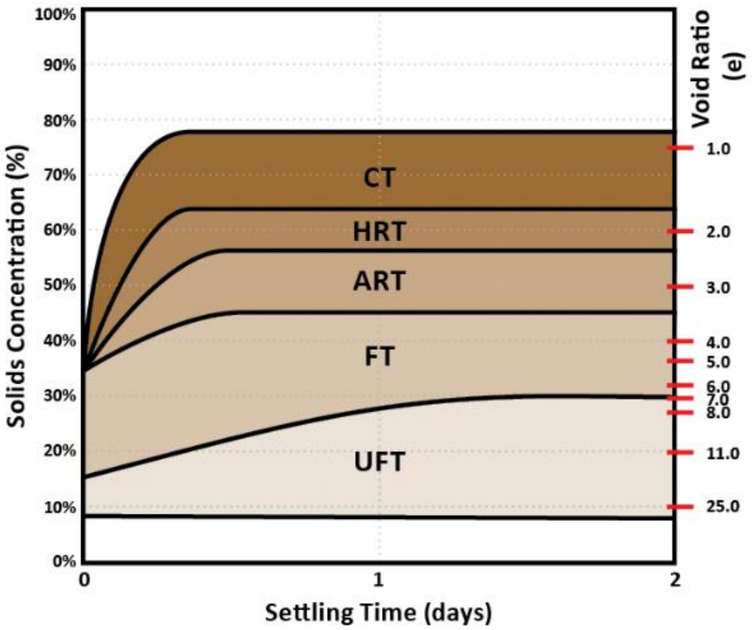


Fig. 2.7
Typical initial settled densities (solids concentration) versus settling time for tailings types (typical void ratios for specific gravity of 2.75 are included for reference)

<u>Settling Tests to Determine Non-Segregating Tailings Density</u>

A segregating/non-segregating boundary is the surface below which the coarse particles settle through the fines-water slurry (segregate), while above it no appreciable segregation takes place. Settling tests can be used to assess the solids concentration at which the tailings become non-segregating. A non-segregating mix can be defined as a slurry in which at least 90% of the fines are retained within the settled tailings. A segregating mix is a deposit in which less than 50% of the fines are retained, whereas partially segregating mixes are those in which the fines retention is between 50% and 90%.

The non-segregating solids concentration can be determined by carrying out settling tests at a range of solids concentration and examining each test to determine if segregation is occurring between the bottom and top of the sample.

<u>Settling tests to confirm tailings and consolidation parameters in the field</u>

Settling tests can be used to calibrate and provide confirmation of the tailings type, as shown on Figure 2.6 and Figure 2.7. The tailings type can then be used in the other charts in this section to determine indicative values of consolidation and hydraulic conductivity parameters. Settling tests can be carried out quickly and inexpensively, hence providing a good idea of the spatial (deposition areas) and temporal variability of the tailings.

Settling tests with application to water balance and water management

The settling test can be used to understand the water balance of the TSF in more detail. For example, the initial settled density of the solids provides the minimum volume of water that will report to the decant pond, recognizing that additional water will be released through consolidation and lost through desiccation if the surface is exposed.

Results from the settling test, i.e., the settling velocity of the tailings, provides guidance for sizing the pond area, required for effective clarification of water for reclaim to the process plant. The degree to which this calculation can be used to manage pond size, and thus recycle rates, is also a function of clay fraction and the tolerance of the process to fines or potentially reagent residues.

2.3.3.2. Drained Settling Tests

Drained settling tests are intended to simulate the effect of drains under, or within, the deposited tailings. The test is carried out in the laboratory using a cylindrical glass tube—similar in dimension to that used in the standard jar test—with a drainage system at the bottom (comprising a layer of glass beads covered by a porous disc and a circular filter of geofabric (or filter paper) at the bottom), and an outlet or bleed pipe.

A sample of the slurry is carefully introduced into the cylinder, ensuring that the basal drainage system remains intact and is undisturbed. The cylinder, bleed pipe, and solids contents are weighed and the initial volume in the cylinder measured. The top of the cylinder tube is covered to minimize evaporation loss. At regular intervals, the solids level, water level, and volume of drained water is recorded. The sample settles until clear supernatant water on top of the settled tailings can be decanted and measured. When underdrainage ceases and solids settlement has substantially stopped, the complete apparatus is re-weighed. The total observed weight loss at the end of the test may simulate potential water loss to downward drainage and initial water recovery from surface drainage.

No- or little- downward drainage could reflect the case where deposition was onto an active beach with fully saturated underlying tailings. Unrestricted downward drainage could reflect the situation where the underlying tailings had time to dry and de-saturate (e.g., a tailings beach with a low rate of rise), such that some of the water released from the tailings drains downward and fills void space rather than bleeding to the surface. The challenge with this test comes in the interpretation of actual conditions, which lie between these extremes. Care should be taken in interpreting these tests, as the underdrainage achieved on a beach in the field is highly dependent on the degree of drying/desiccation of the underlying layer and in sub-aqueous tailings in the configuration of the drainage system, particularly the lamination/cross bedding of the deposited tailings.

2.3.3.3. Air Drying Tests

Settling tests can be extended to assess the effect of air drying/desiccation on the deposited tailings and to understand the rate of desaturation in a beach deposit. These tests are particularly useful for tailings in arid environments. There are no standards for this test work and, consequently, the laboratory tests should be designed to simulate what may happen in the field.

- The tailings sample at a representative solids concentration can be placed in a glass cylinder and dried under natural conditions or, alternatively, dried under heat lamps to develop an evaporation rate that would simulate field conditions. Ports can be placed in the side of the cylinder to collect samples at various depth and to determine the moisture content and density with time.
- Another method involves depositing a thin layer of tailings at a representative solids concentration in a series of open pans/containers and, after settling, carefully decanting surface water to expose the surface to controlled airdrying. It is normal practice to run a series of tests in parallel under the same conditions to enable sampling and testing without destroying the principal test material. Density and moisture content are logged at frequent intervals, and the key stages of drying monitored to achieve the tailings properties at the minimum density, bleed point and tailings crack points. The resulting data provide the critical points for determining bleed time and achievement of 85% saturation and are thus helpful in designing deposition cycle times for disposal, particularly for finer deposits in arid environments.

Various numerical models have been developed to predict the tailings behavior using such results. However, of primary importance is the need to establish parallel sampling and testing programs during deposition, to refine the design assumptions and optimize deposition plans to maximise consolidation and drainage.

2.3.3.4. Consolidation

Consolidation is a process by which soils decrease in volume due to self-weight, or under applied stresses. During this process, soils densify under increasing effective stress through the dissipation of excess pore pressure. The boundary between settling and consolidation is not uniquely defined, will be transitional with depth, and is dependent on the initial void ratio. For practical purposes, the end of settling, at effectively zero effective stress, can be considered as the onset of consolidation. Consideration should also be given for secondary consolidation/creep behaviour for fine grained soils.

One of the most common problems encountered in oedometer tests on tailings is that the test cannot be applied to a slurry. Testing from a slurry state from low stresses requires specialized equipment, such as a large strain consolidation test or a slurry consolidation test. Undertaking parallel oedometer testing on tailings samples—using reconstituted samples to replicate successive stress stages — is recommended, to characterize the effective stress/consolidation properties. It is important that the engineer understands the limitations of these tests and that the data produced, though a good indicator of the stress /consolidation history of a tailings deposit, requires experienced interpretation of the results due to the significant heterogeneity that is exhibited in tailings deposits.

Testing at low stresses provides a basis for understanding the rate of water release during settling on the beach and the active consolidation water release. These are important considerations, especially in arid environments, for assessing evaporation losses.

Figure 2.8 shows the relationship between the void ratio and effective stress for the various tailings types, and Figure 2.9 shows the relationship between the coefficient of consolidation (C_V) versus effective stress.

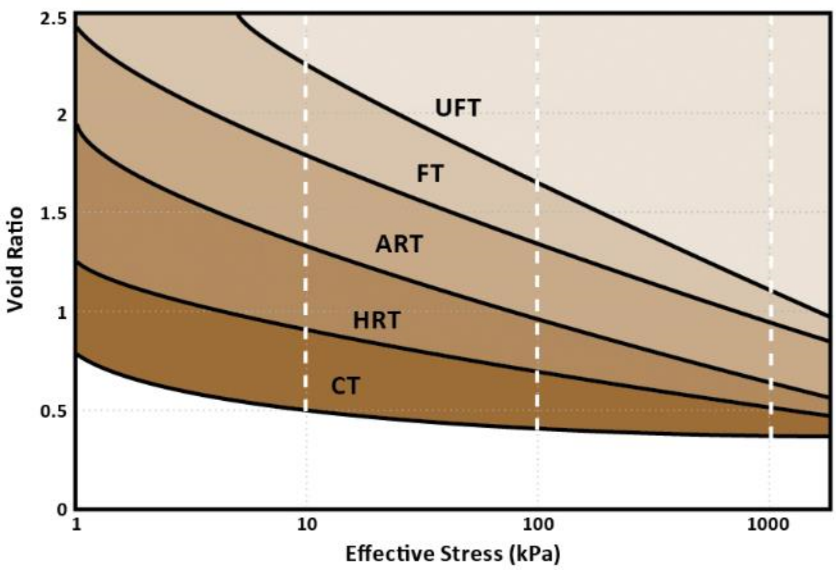


Fig. 2.8

Void Ratio versus effective stress for tailings types

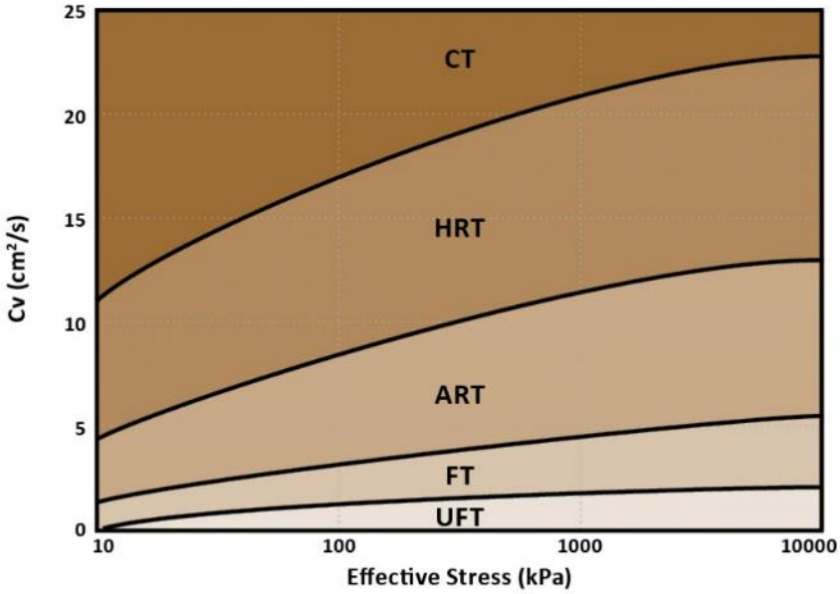


Fig. 2.9
Coefficient of consolidation (Cv) versus effective vertical stress for tailings types

2.3.4. Density

The dry density of tailings can be determined in the laboratory from settling, consolidation, and desiccation tests. The density of deposited tailings can also be interpreted from Figure 2.7, which shows typical void ratio versus effective stress, through correlation with the graphs shown on Figure 2.4 and Figure 2.5, which show the relationships between dry density, void ratio and solids concentration for different specific gravities. These correlations should be used for preliminary studies and supported by a properly prepared program of laboratory testing and field verification.

2.3.5. Hydraulic Conductivity

Hydraulic conductivity (often simply called hydraulic conductivity) testing of tailings can be carried out in the laboratory using: (1) permeameter or flexible wall permeameter; and/or (2) consolidation or triaxial test interpretations. However, the hydraulic conductivity of the tailings deposit is a function not only of the particle size distribution and density, but also of the structure developed during deposition. As this structure is generally difficult to replicate in the laboratory, caution is required when interpreting laboratory hydraulic conductivity results. The following important factors should be considered:

- The potential segregation of tailings as they are deposited will affect the spatial variation in hydraulic conductivity. This may require testing of the range of segregated tailings that could be derived from the jar settling tests described in Section 2.3.3.1.
- The hydraulic conductivity will vary with the tailings type and the effective stress, as shown on Figure 2.10.
- The hydraulic conductivity also varies with the fines content (%<63 μm to 75 μm) of the tailings. A typical plot of fines content versus effective stress for the various tailings types is shown on Figure 2.11. Care must be exercised in using the percent fines, as the clay fraction will dominate the hydraulic conductivity of the tailings. Thus, this figure provides only general guidance.
- Finally, the hydraulic disposal of tailings, even sub-aqueously, will result in a laminated deposit with the potential for the development of both horizontal and cross-bedded components. This leads to a high degree of anisotropy with enhanced k_h/k_{vtsf} ratios, which are typically on the order of 10 but may exceed 20. This important design parameter is difficult to determine from reconstituted samples and is best estimated from case histories of tailings dam performance. Indications of k_h/k_v can be interpreted from in situ dissipation tests in conjunction with CPT with pore pressure measurement (CPTu).

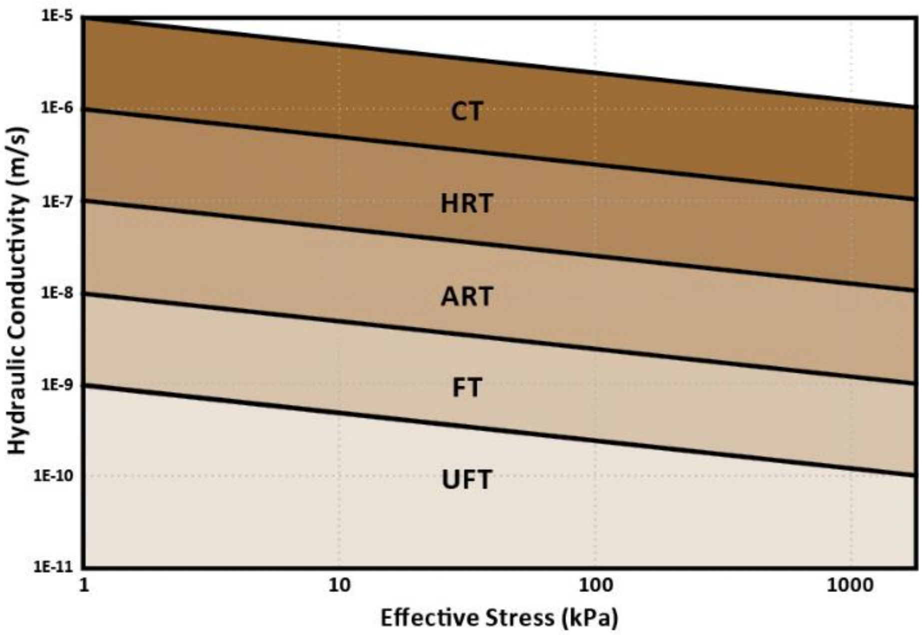


Fig. 2.10
Hydraulic conductivity versus effective vertical stress for tailings types

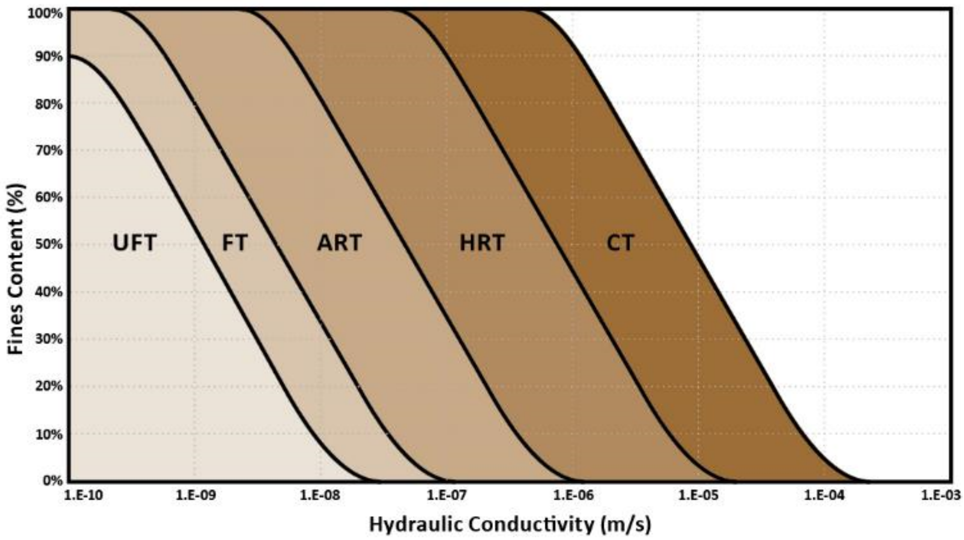


Fig. 2.11
Fines content versus hydraulic conductivity for tailings types

2.3.6. Strength

Shear strength corresponds to the maximum shear stress the tailings can resist under normal stress conditions and at the prevailing water content and density—a fundamental parameter in defining the structural stability of the tailings. As with all geotechnical tailings tests, the representativeness of the sample and the testing method are crucial in estimating geotechnical parameters. Therefore, both sample condition and test method are key factors during laboratory testing.

Triaxial testing

During the determination of shear strength in the laboratory using triaxial equipment, loading beyond the maximum stress results either in the loss of strength and collapse of the sample, or in the accumulation of large plastic strains. The shear strength of tailings depends on whether shearing occurs in a drained or undrained state, as well as the ability of the tailings to accommodate levels of strain and deformation. When considering the shear strength, therefore, it is important to differentiate between drained and undrained strength:

- Drained strength is associated with a rate of shearing sufficiently slow to ensure full dissipation of excess pore water pressures. Shearing takes place at constant pore water pressure and effective stress and is accompanied by an increase or decrease in volume, depending on initial density and confining stress.

- Undrained strength, on the other hand, corresponds to the condition where the rate of shearing is high enough to prevent drainage. In this case, there can be no volume change and shearing is accompanied by an increase in pore water pressure and associated change in effective stress.

In the laboratory, the drained shear strength of a material is normally obtained by means of consolidated drained (CD) or consolidated undrained (CU) triaxial tests, with pore water pressure measurements to plot the results in terms of effective stress. Consolidated undrained tests can also be used to obtain the ratio of undrained shear strength, s_u, to effective vertical stress, σ_v'. However, of paramount importance is the selection of the sample for testing and the assessment of its representative characteristics (gradation and density) in relation to its location in the TSF. In summary:

- Quick undrained (QU) tests include the unconfined compression and the triaxial compression test for which there is no drainage during the application of the confining pressure or during axial loading, and the strength obtained corresponds to that associated with no change in water content.
- Undrained (UU) triaxial tests are like the QU test but includes measurements of pore water pressure.
- Consolidated undrained (CU) triaxial tests allow the sample to consolidate to a given effective stress before applying loading in the undrained condition. Measurement of pore water pressures allows determination of both drained and undrained strength parameters.
- Cyclic triaxial tests involve cyclic loading to simulate earthquake loading and derive the number of cycles required for collapse (liquefaction) of the sample.
- Static simple shear and cyclic simple shear tests, are plane strain tests, with shear strain induced by horizontal movement at the bottom of the sample relative to the top. The test allows consolidation and shearing of a sample under constant volume conditions.
- Consolidated drained (CD) triaxial tests allow the sample to drain freely during consolidation and loading stages and is also used to measure drained strength.

Direct shear tests, which include the shear box and ring shear test, can determine the drained strength of tailings if the rate of strain is slow enough to permit drainage. Additionally, a modification of the ring shear test equipment may be used to indicate residual strength, a particularly important parameter in determining the dam breach runout behaviour under static or seismic liquefaction. Repeated direct shear tests may also indicate residual strength.

The laboratory vane shear test can be used to obtain the peak and remoulded undrained strength of soft tailings.

When evaluating the stability of the tailings dam, it is important to ensure that the correct strength parameters are obtained and that these are employed in an appropriate drained or undrained strength analysis.

2.3.7. Thickening and Filtration

Thickening test work in a laboratory or pilot-scale dynamic thickener unit produces design parameters that can be directly scaled up to a full-scale thickener. Typically, the impact of flocculant dosage and solids loading rate ((t/h)/m²) are expressed in terms of achieved thickener underflow solids mass concentration and overflow clarity; in other words, the separation efficiency. The solids loading rate is the hourly tonnage of tailings that can be processed by one m² of the cross-section area of the thickener.

Filtration equipment manufacturers and engineering firms commonly have databases of filtration performance information that can provide approximate indications of performance. Predictive models to estimate filtration performance—sufficiently accurate for full scale design—do not exist. (Kujawa, 2015). Laboratory and pilot scale test work are a necessity for equipment sizing and filtration performance evaluation.

Filtration test work should be designed to produce all the necessary design parameters for sizing of the full-scale equipment, regardless of filtration equipment supplier, or brand. As in the case with thickening, the test work should be designed to map out the full operating response window for filtration by investigating the main filtration variables. The parameters tested depend on the method of filtration and the project circumstances but, as a minimum, include measuring the filter cake moisture as a function of cake thickness and drying time. The results are used to achieve the target cake moisture at the highest possible filtration rate ((/h/m²)—and the lowest capital cost—for the chosen filtration method.

By mapping out the full dewatering response window for different dewatering methods, trade-off studies may determine the most cost-effective dewatering “transfer point” between thickening and filtration.

Typical yield stress versus solids concentration for the tailings types are presented on Figure 2.12, along with indicative yield stresses for different degrees of thickening.

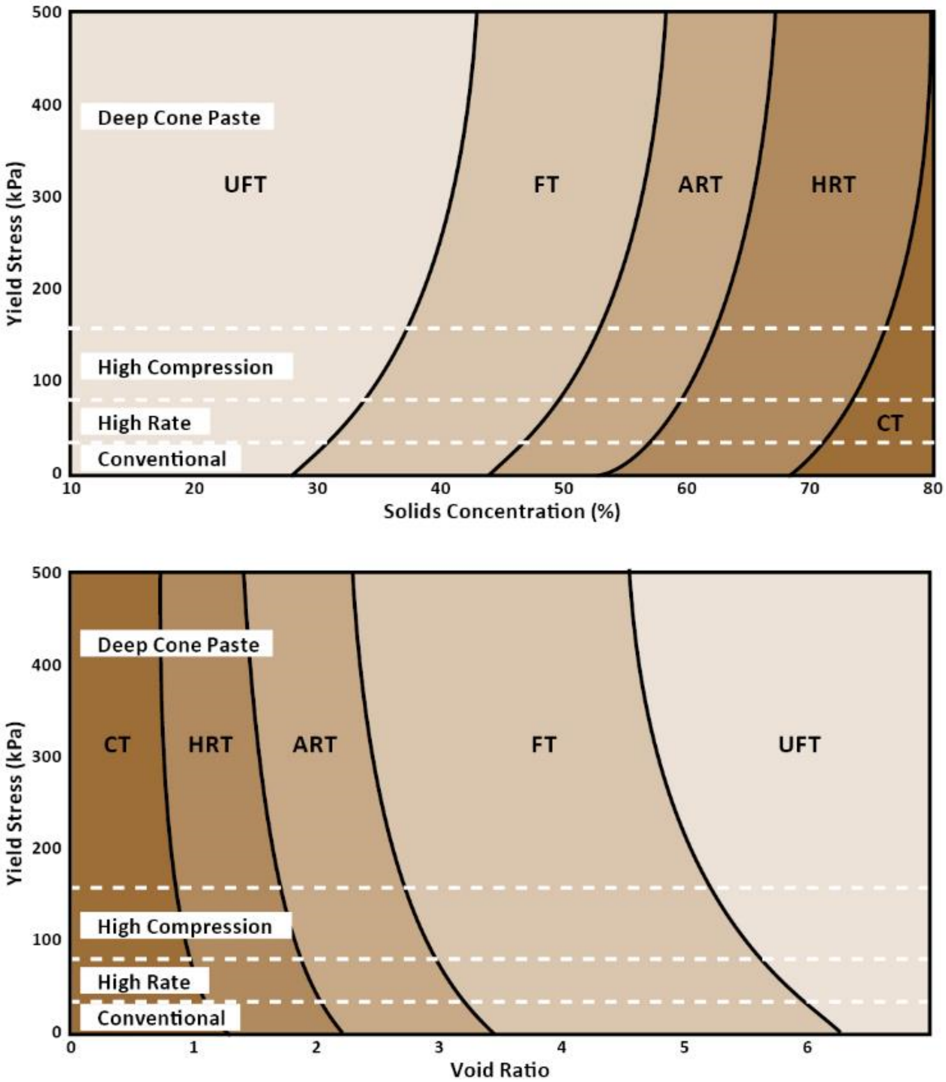


Fig. 2.12

Yield stress versus solids concentration and void ratio for tailings types

2.3.8. Geochemical Properties

2.3.8.1. Introduction

Geochemical characterization of tailings is required to determine the potential for metal leaching and acid rock drainage (ML/ARD) (also known as acid and metalliferous drainage (AMD)) under both neutral and acidic conditions, respectively. Tailings characterization should be carried out in conjunction with process water quality testing, and the testing should recognize the potential for longer-term geochemical changes. Geochemical testing typically proceeds with static testing, followed by kinetic testing, to assess metal leaching. As with geotechnical characterization, sample selection and sample representativeness are important to allow extrapolation of the testing to the orebody and the deposited tailings over the life of the TSF.

Geochemical characterisation of tailings is a key issue during permitting of any proposed containment facility, particularly in well-regulated environments. ARD occurs when reactive sulphides contact with oxygen and water in the presence of iron/sulphur-oxidising bacteria, and there is insufficient or ineffective alkaline material to neutralise the products of oxidation and formation of acid. ARD is a dynamic and spatial phenomenon, and acid conditions occur if the acidity generated is greater than the neutralisation capacity of the system at any stage of the life cycle of sulphide oxidation, both during the deposition period and post closure. The term "ARD" is applied to the resulting leachate, seepage, or if drainage is acidic, typically defined as pH less than 6. There is extensive literature concerning tailings characterisation and ARD and a significant amount of knowledge has been documented. This may be referenced using the conferences and websites summarised in Table 2.4, and other best-practice documents. There are also many scientific journals that publish research on ML/ARD or related subjects.

Table 2.4
Organizations and References (Reference European Handbook on Hydraulic Fill 2014)

Description	Examples of References
Canadian Mine Environmental Neutral Drainage (MEND) program started in 1989 has an extensive library of studies on ML/ARD (AMD).	http://www.mend-nedem.org/default-e.aspx
Global Acid Rock Drainage (GARD) Guide sponsored by International Network for Acid Prevention (INAP).	This document is easily accessible via the internet: Office of Surface Mining Reclamation and Enforcement of the USA
International Network for Acid prevention (INAP). An international organization led by the major mining companies. It is supporting research on the subject and sponsored the GARD Guide.	http://www.inap.com.au/index.htm
International Conferences on Acid Rock Drainage (ICARD).	http//www.mend-nedem.org/default-e-aspx
Sudbury Mining & the Environment International Conferences	http//www.mend-nedem.org/default-e-aspx
European Commission Hazardous Waste	ec.europa.eu/environment/waste/hazardous_index.htm

Geochemical characterisation of mine tailings is a pre-permitting requirement in many jurisdictions. The Mine Waste Directive (2006 21, European Union), for example, cites Prevention of Water Status Deterioration, Air and Soil Pollution as one of the justifications for the characterisation programme. The Commission Decision 2009/360/EC provides a framework for the characterisation programme to form the basis of the Waste Management Plan. Geochemical characterization on a mine project is also considered international best practice. The objectives of characterisation are generally stated as:

- Prevention or reduction of waste production and its harmfulness by considering (among other factors) changes that the tailings may undergo in relation to the method of storage or an increase in surface area and exposure to conditions above ground.
- Description of expected physical and chemical characteristics of the tailings to be deposited in the short and long-term, with reference to their stability under surface atmospheric/meteorological (e.g. freezing, drying wetting, etc.) or storage conditions, taking into account the type of minerals that which will be processed to produce the tailings.
- Prevention of water quality deterioration by evaluating the potential to generate leachate, and the contaminant content, of the deposited

tailings during both the operational and post-closure phase of the waste facility.

To comply with waste characterisation objectives, it is often a requirement to determine whether:

- The tailings are “inert”, e.g., adopting the European Union criteria defining “inert” waste (Commission Decision 2009/359/EC);
- The tailings have potential for acid generation and, if so, how it will be realised; or
- There are metal leachability issues.

A characterisation programme is thus required not only for the tailings to be deposited, but in anticipation of future waste material characteristic and temporal behaviour changes, likely during the operational and post-closure phases. The methodology is typically iterative, and careful consideration must be given to all the information available and to the variability of the ore deposits and the different leaching rates.

The number of samples that need to be tested depends on the likely variability of the tailings and other mine wastes to be incorporated into the TSF, and to be generated over the life of the project. Mineral processing plants are designed for an optimum ore composition, but some deposits can change significantly over the life of the project. Therefore, samples must be representative of the material to be deposited, but it must also be recognised that samples generated in a pilot plant might not necessarily simulate full-scale plant production. It is therefore important to understand any deficiencies in the representative nature of the samples from the onset of the project.

Another practical problem associated with sampling, is that the limited quantity of tailings generated from pilot plants may not be sufficient for either geochemical characterisation or for geotechnical testing. This issue must be addressed if the material characterisation is to be based on internationally acceptable sampling criteria. In some cases, samples of ore can be used as surrogates for tailings, if there are not many changes in mineralogy expected from extraction in the processing plant.

2.3.8.2. Static Testing

Static testing is carried out to provide a general assessment of the ML/ARD potential and typically constitutes a suite of testing, which may include:

- Acid base accounting (ABA) which characterizes the acid potential (AP), represented by the oxidizable effective sulphide content and the effective neutralization potential (NP) (or acid neutralization capacity (ANC)), representing NP that will maintain pH values in contact water that are greater than, or equal to, 6. A general classification, is shown in Table 2.5. (However, note that other methods for classification are in general use).

- Mineralogical analysis including quantitative or semi-quantitative sulphide and carbonate minerals, carbon speciation, and whole rock analysis.
- Leach tests (shake flask).
- Net acid generating (NAGpH) tests.
- Analog data sets from existing ore bodies with similar geology and mineralogy.
- Short-term leachability tests—note that some of these tests can be used to classify the samples as hazardous or non-hazardous using criteria developed by regulators, e.g., the BC Waste Management Act, Canada or the US Environmental Protection Agency.

Table 2.5

ARD risk classification based on net potential ratio (NPR)

Classification	Potential of ARD	Screening Criteria	Comments
Potentially Acid Generating (PAG) or Acid Generating (AG)	Likely	NPR less than 1	Likely acid generating unless the sulphides are non-reactive.
Uncertain (and requires further characterization)	Uncertain	NPR between 1 and 2	Possibly acid generating if: • Neutralization potential is insufficiently reactive: or if • Neutralization potential is depleted at a faster rate than the sulphides.
Not-Potentially Acid Generating (not-PAG)	Low	NPR greater than 2	Not-PAG unless: • significant oxidation of sulphides occurs on preferentially exposed grains within fractures, or • the sulphides are extremely reactive in combination with insufficiently reactive NP.

Source: Based on MEND (2009)

Note: 1) NPR – Net potential ratio = acid neutralization potential/ acid production potential

Inert waste

In some cases, it may be possible to classify the tailings as “inert”. For example, inert tailings in the European Union (Commission Decision (2009/359/EC)) are defined as follows:

- *“Maximum sulphide-sulphur content of 0.1% or sulphide-sulphur content of maximum 1% if the neutralization potential ratio is higher than three based on the results of EN 15875 static testing.*
- *There is no risk of self-combustion and the tailings will not burn.*
- *There are no substances potentially harmful to the environment or human health (specifically mentioned As, Cd, Co, Cr, Cu, Hg, Mo, Ni, Pb, V and Zn).*
- *The waste is substantially free of products used in extraction or processing which could harm the environment or human health*.”

Static testing should be the first phase of geochemical characterization, unless it is demonstrated that the tailings are inert and non-reactive.

2.3.8.3. Kinetic Testing

Kinetic testing assesses metal leaching and acid generation rates and intensity in materials that become acidic during the test period. Kinetic testing can be carried out in the field or in the laboratory. Two main types of apparatus are used for kinetic testing in the laboratory, namely humidity cells and columns. Field testing has the disadvantage of being less controllable and may take longer to generate the required data, although it may also present the most representative conditions. This emphasizes the need for early characterization of the tailings.

Kinetic tests provide a measure of the “reactivity” of exposed minerals and test whether the sample will generate net acidity at any point in time. The primary rates of acid generation, neutralisation and metal release are the main parameters obtained from kinetic testing. This testing needs to be designed carefully, and metal leaching and depletion time results and tests may be available within a few weeks to tens of weeks. The use of experienced professionals in the interpretation of the results is paramount.

The range of tailings classification is described below and illustrated on Figure 2.13 and Figure 2.14.

Aqueous-based Classification:

- Acid Rock Drainage (ARD): pH less than 6.0.
- Neutral Mine Drainage (NMD): pH greater than 6.0 and total dissolved solids (TDS) less than 1000 mg/L. Saline Drainage (SD): pH greater than 6.0 and TDS greater than 1000 mg/L.

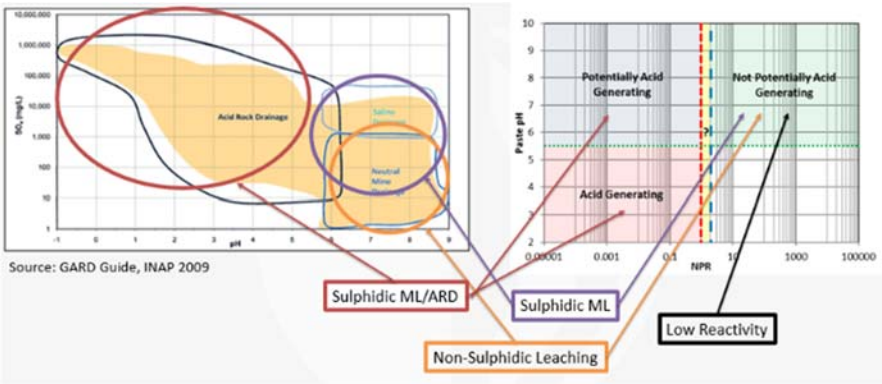
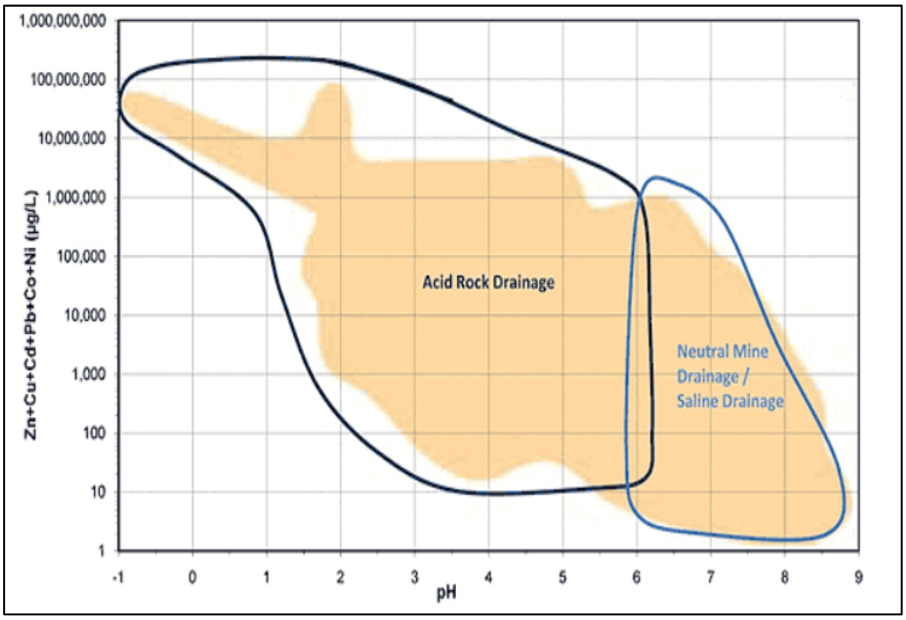


Fig. 2.13
Ficklin-style diagram showing ARD, NMD and SD and relationship with past pH and NPR (Klohn Crippen Berger 2017)



Source: GARD Guide (INAP 2009)

Fig. 2.14
Ficklin-style diagram showing ARD, NMD and SD fields as a function of pH and dissolved base metal concentrations (Klohn Crippen Berger 2017)

2.4. IN SITU TAILINGS PROPERTIES

2.4.1. Introduction

This section of the Bulletin summarizes the key aspects of field behavior of tailings. While the in situ properties of deposited tailings may be extrapolated from laboratory testing with considerations of empirical field data from existing tailings facilities, they will be heavily influenced by a range of operational conditions that cannot be simulated in the laboratory and can vary significantly between sites and operational conditions.

In addition to the types of tailings (Table 2.1), the field behavior is influenced, for example, by the solids concentration of the tailings, climate, deposition methods, and ore and process plant variability. Higher slurry solids concentrations result in reduced segregation of particles and less layering of finer and coarser tailings. Cold climates can hinder consolidation and allow formation of ice lenses (permafrost) and glaciation of tailings beaches, whereas arid climates promote consolidation by desiccation. Mill (thickener) upsets can lead to periods of low solid concentrations, which can result in flatter slopes and increased segregation.

Testing in the laboratory at the pre-operational stage, where sample availability is often restricted and field conditions are not reasonably simulated, should be followed up with testing during the life of the mine to confirm the tailings properties under actual operating conditions.

2.4.2. Beach Slopes

Slope data for beaches above the water pond have been collected from numerous tailings projects worldwide and Figure 2.15 provides a plot of beach slope angle versus the distance from the discharge point for the various types of tailings and degrees of thickening. The main observations from these data are:

- Coarser tailings have steeper slopes grading down to near horizontal slopes for ultrafine tailings;
- Beach slopes are typically concave, with hydraulic sorting of particles down the beach according to their particle size and specific gravity;
- Thickening to a higher solids concentration increases the beach slopes, particularly over short distances, and, reduces hydraulic sorting down the beach.

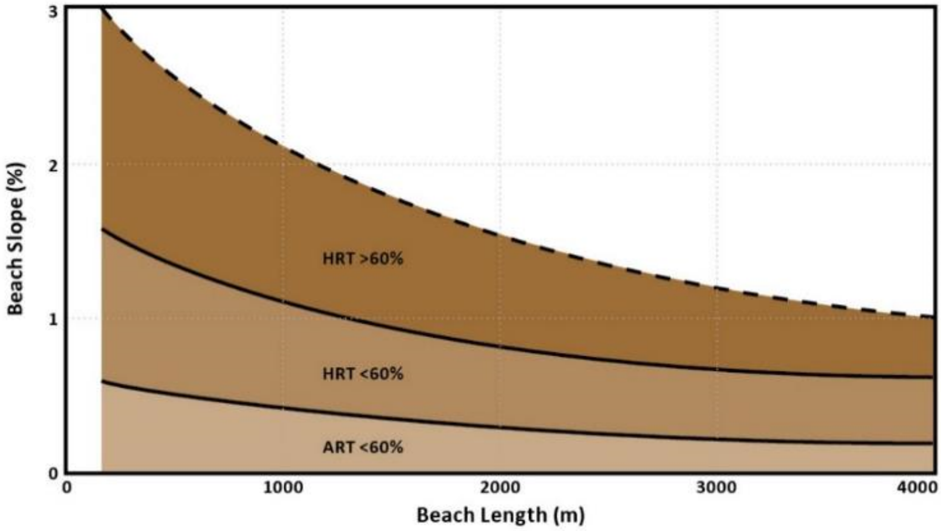


Fig. 2.15
Beach slope (%) and tailings discharge distance relationship for tailings types

The concave shape of the beaches is principally due to segregation, sedimentation, and consolidation of the tailings as they are transported down the length of the beach. Additional factors influencing the beach slope are the variability of the ore type and the performance of the thickeners. Upset conditions such as finer tailings due to localized clay rich zones in the ore, for example, or loss of flocculant control in the thickeners, can result in flatter slopes, which then require a return to pre-upset conditions to establish the original beach slope.

Climate may influence the beach slope, with arid climates increasing the rate of consolidation, as evaporation occurs along the beach length. In arctic climates, tailings may freeze before they reach the reclaim pond, which shuts down the consolidation process and may locally steepen the beach. Locally steepened slopes may become unstable during the thaw period.

The velocity of the deposited tailings has a local impact on the steepness of the beach. Reducing the velocity by discharging from a greater number of smaller spigots results in a locally steeper beach.

Sub-aqueous beach slopes are controlled by the settling behaviour of tailings in water. As the tailings contact the water pond the particles settle according to conventional settling characteristics, initially forming a steep slope as the coarse particles settle. Underwater beach slopes typically vary from 3% to 5% for Hard Rock and Coarse tailings to <0.7% for Altered Rock and <0.4% for Fine tailings. After the initial steep underwater beach slope, the slopes typically flatten to <0.5%.

2.4.3. In Situ Tailings Density

The achieved density of the impounded tailings plays a dominant role in planning the tailing facility capacity and construction sequence. Assumptions on the density are made during the design phase based on laboratory testing and comparison to example data on Figure 2.7. The void ratio can be related to the percent solids by weight and dry density with the use of Figure 2.4 and Figure 2.5. Estimation of in situ densities can also be supported with consolidation modeling of the variation of tailings within the impoundment and the loading conditions

Verification of the density is required after the start of the operations and the average density of the deposit typically increases with time, as tailings consolidate under their self-weight. Frequent estimates of the density are recommended during the initial years of facility operation. This involves estimating the volume of the deposited tailing using the impoundment survey prior to tailing disposal and a current impoundment survey. The total dry tonnes of tailings deposited by the survey date are then divided by the occupied volume to estimate the average density of the impounded tailings.

Tailings go through various stages of settlement and consolidation once deposited on a beach or within a water pond. These stages depend on the properties of the tailings, how they are discharged, and climate. For tailings discharged at a relatively low solids concentration, there will be significant initial release of excess pore water as the tailings settle. There will also be segregation by particle size and density, resulting in effectively different tailings properties along the length of the beach. This segregation results in grading variations horizontally down the beach, but also vertically, where layers of finer and coarser materials become layered due to streams of tailings meandering across the beach.

Following release of the initial “bleed water,” tailings will continue to consolidate, and the surface will dry (desiccate) with exposure to evaporation or freezing. Consolidation can also occur during freeze/thaw cycles in cold climates. In fine-grained tailings, drying can lead to the development of suctions forces within the pores, which increase the density of the tailings as drying and shrinkage occurs. This is accompanied by surface cracking. The drying process is most effective when thin layers of tailings are deposited and allowed to dry prior to placing the next layer. If layers are placed too thickly, the tailings at depth will experience limited desiccation.

Eventually, a maximum air-dried density is reached, and further densification cannot occur unless the dried soil structure is broken up by mechanical means.

2.4.4. Hydraulic Conductivity

The in situ hydraulic conductivity of a tailings deposit is a function of the type of tailings, the percentage of fines — particularly the clay component — and the deposition system employed. For example, a well controlled beach deposit can develop a laminated interbedded structure similar to shallow lacustrine deposits. Segregation on the beach and varying deposition pathways can result in coarser, higher hydraulic conductivity layers. The impact of the cross bedding, combined with the small, but noticeable differences in settlement rate across the beach, results in a highly stratified anisotropic layer system, which exhibits an enhanced k_h/k_v ratio of 10 - 15 or higher. While this anisotropy can be beneficial in enhancing drainage, it also makes in situ measurement of hydraulic conductivity problematic. It is noted that the interbedding is not restricted to subaerial tailings, but also occurs in subaqueous deposits. The formation of gypsum deposits in high pH tailings deposits, or products from the processing wastes, may also impact in situ permeabilities.

Assessment of hydraulic conductivity by in situ testing is challenging. In some cases, surface infiltrometer tests can provide data, if available. The interpretation of the CPT data must be analysed appropriately, and the results treated with caution. Reference should also be made to case histories that back-calculate k_h/k_v from performance data that is useful to provide further support.

2.4.5. Shear Strength – Drained and Undrained, Static and Dynamic – Critical State Soil Mechanics

The drained strength of most tailings is relatively high, as the tailings are usually a product of crushing rock, which commonly results in angular competent particles. Drained friction angles typically vary from 30° to 35° or higher, although the drained strengths of fine and ultrafine tailings are lower. However, drained strengths rarely control the strength of tailings, because as failure is initiated the tailings behave in an undrained state, with generation of pore pressures. An understanding of the behaviour during undrained loading is best illustrated with critical state soil mechanics (Jeffries & Been, 2018). Critical state can be viewed as the ultimate condition that will be achieved after sufficient shear. Tailings behaviour ranges from contractant (loose) to dilatant (dense) states and the boundary between these is commonly referred to as the critical state line, as illustrated on Figure 2.16, which plots void ratio against mean stress. The further the tailings density is from the final critical state, the faster dilation or contraction occurs. The state parameter ψ is defined as a measure of that deviation, as illustrated on Figure 2.16.

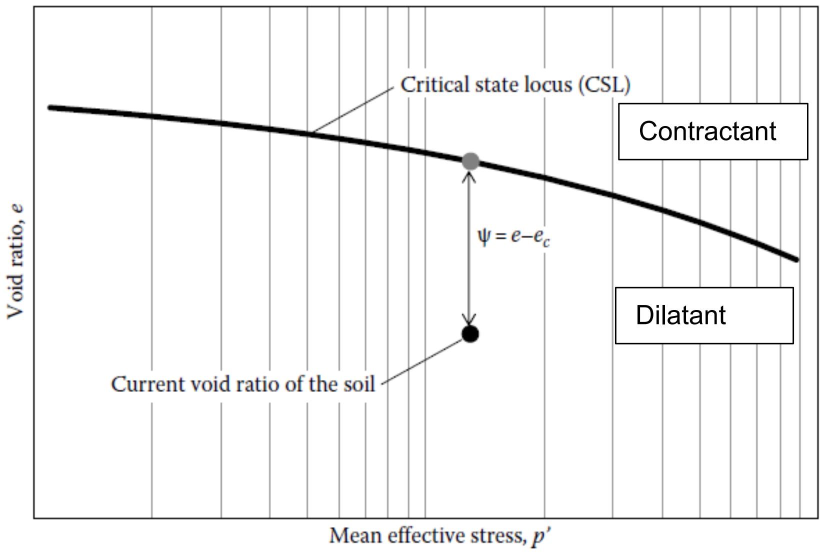


Fig. 2.16
State parameter (ψ) and critical state line (after Jefferies & Been 2016)

Determination of ψ has been advanced with the development of CPT technologies in which laboratory tests have been correlated with CPT testing to develop a relationship to determine ψ. A value of $\psi < -0.05$, is typically used to identify contractive soils. CPT has also been developed to determine peak and residual undrained shear strengths where the cone tip resistance and side friction have been calibrated with empirical and laboratory data (Robertson, 2010).

Laboratory determination of the peak undrained shear strength of in situ tailings is challenged by the difficulties in collecting representative undisturbed samples, and typically CPT is the primary assessment tool. Estimation of in-situ pore pressures is also required to estimate the C_u/σ'_{vo} ratio. In situ pore pressures within tailings and/or foundation are seldom hydrostatic and may be higher than hydrostatic for under consolidated soils or lower than hydrostatic where strong underdrainage is present. The peak undrained shear strengths of tailings from CPT assessments typically vary from $C_u/\sigma'_{vo} = 0.25$ to $C_u/\sigma'_{vo} = 0.3$. Higher peak undrained shear strengths (up to $Su/\sigma_v' = 0.5$) may be obtained through drying of the tailings or with development of structure due to chemical processes. Lower values of C_u/σ'_{vo} (< 0.15) may apply to fine and ultrafine tailings. Peak and residual undrained shear strengths can also be obtained with in situ vane shear tests.

Static or flow liquefaction can occur when the peak undrained shear strength is exceeded, which can be triggered with changes in stresses due to, for example: dam raises, stress concentrations (particularly at higher dam heights), extension stress paths due to different material behavior, or from unloading. The state of practice for assessment of static liquefaction continues to evolve and tailings specialists are cautioned against assuming that the process is well understood. Accordingly, it is often prudent to assume that when contractant soils are present, static liquefaction could occur, and to design for the residual shear strength.

Case histories of static and seismic tailings liquefaction flow slides generally involve tailings deposited in a loose state and at shallow depths up to 20 m deep, with low consolidation stresses less than 200 kPa. Such tailings were highly contractive in shear and exhibited high "brittleness" with a residual (or large strain) undrained shear strength as low as 10% of the peak undrained shear strength. The high brittleness contributed to both the suddenness of the liquefaction events and the mobility of the consequent tailings flow slides. Moreover, recent case histories indicate that loading or straining conditions leading to extension stress paths in tailings may be a more critical triggering condition than previously appreciated in the industry.

Estimation of the residual undrained shear strength can be obtained using CPT and laboratory testing, although obtaining representative data is challenging. Empirical data from past failures can be used to guide the designer and typically are of the order of $C_{ur}/\sigma'_{vo} = 0.1$, with a range of $C_{ur}/\sigma'_{vo} = 0.05$ to $C_{ur}/\sigma'_{vo} = 0.15$.

The behavior of tailings under high stresses has important considerations which include:

- Consolidation of tailings at high stresses leads to a reduction of void ratio which generally increases strength, but this is often counteracted at very high stresses (likely greater than 500 kPa to 1000 kPa) by crushing of the particles at their points of contact during shear. The net effect is a general reduction in the peak effective friction angle with confining stress, even for tailings deposited in a dense state, such as compacted cyclone sand (Busslinger et al., 2013). More importantly, compression of a loose tailings structure at high stresses can beneficially reduce the contractive behavior of tailings leading to a lower degree of brittleness (Robertson, 2017) and such reductions in brittleness may account for the absence of tailings flow-liquefaction case histories at depths greater than 20 m. Testing of loose samples of tailings at high stresses may be beneficial for some projects where high stresses are applicable.
- Tailings that exhibit apparent over consolidation due to desiccation or mineral precipitation may lose their structure under higher stresses, leading to a brittle structure, with a strength reduction that could revert to normally consolidated tailings. In this case, the soil would generate excess pore pressures when loaded.

2.4.6. Over Consolidation Ratio

Maximum past stress or apparent over consolidation ratio (OCR) is another important consideration for estimating the shear strength of tailings and/or underlying clay foundation. Understanding the OCR behaviour of clays is well documented (e.g. SHANSEP method) with standard soil mechanics. However, tailings may develop an apparent OCR due to physical or chemical processes that occur during deposition and exposure to the atmosphere. This apparent OCR may indicate higher C_u/σ'_{vo} ratios, however, there remains some uncertainty if the material will behave more brittle and whether the apparent OCR may be reduced under certain stress conditions.

2.4.7. Geochemical Effects

A key facet of the hydraulic deposition of tailings is that geochemical processes may induce physical changes in the tailings. In sub-aerial deposits, even moderate levels of sulphides or salts in the tailings may lead to the development of a thin chemical crust across exposed surfaces where oxidation or selective precipitation occurs under atmospheric conditions. Such crusts are generally thin and have limited competence where the chemical content is nominal and, if left undisturbed, often result in increased runoff rates as well as acting as a very effective dust suppressant. The chemical layers reduce vertical hydraulic conductivity and will thus affect both the rate of desiccation from the exposed tailings surface and infiltration as subsequent tailings disposal takes place. The most noticeable impact may be the resulting flatter beach slopes and lower deposited densities. Further, in beaches that include a structural function, there is the risk that the shear strength along these chemically-altered surfaces may be different from that achieved in laboratory testing. However, the competence of these chemical crusts is, under most circumstances, fragile, and the surface is readily destroyed by vehicles and operators accessing the surface, thus negating the above effects. In extreme cold weather the development of ice lenses in the tailings surface, and the subsequent expansion of the surficial layer, will have a similar effect in destroying the competence of the crust. It is noted that the creation of a chemical crust to act as a dust suppressant is encouraged on some sites by the application of either admixtures or biodegradable oils.

Finally, on large tailings facilities with long deposition rotation times, and for residues with high sulphide contents, prolonged exposure can lead to oxidation of minerals and the development of a “hard pan” across the tailings beach. These surfaces are often hard and compact and are not readily destroyed by vehicular or human access. This may result in a highly-laminated deposit comprising alternating bands of extremely hard, chemically-induced layers and softer, only partially consolidated, tailings with significant vertical variation in geotechnical properties.

The potential for chemical changes in a tailings deposit and their impact on the geotechnical characteristics of a tailings beach must be considered not only in design but also during closure planning, particularly where non-sulphidic or non-PAG tailings are to be employed as the final cover material.

2.4.8. Structural Effects

Leaching of targeted minerals and elements from the parent rock, for purposes of ore recovery, may significantly alter the micro-texture of the individual tailings grains and their interactions. The removal of the targeted substances leaves micro-voids in the tailings grains, which makes the grain surface unnaturally rough. This microscopic roughness influences the geo-mechanical properties of the tailings such as shear resistance and consolidation parameters. This effect has been observed in alumina and uranium industries, where the ore beneficiation includes aggressive chemical processes.

The altered, microscopically rough tailings may exhibit a sand-like behaviour, although the classification tests, described earlier, suggest silty/clayey materials. Such tailings can have a very high friction angle and lower than expected coefficient of consolidation. As a result, the microscopically rough tailings may form high void-ratio matrices of interlocked particles, which are highly resistant to drained shearing, but potentially susceptible to liquefaction.

The micro-texture of the tailings grains can be confirmed by Scanning Electron Microscope (SEM) imaging. SEM should be used where the mineral processing may impact on the tailings micro-texture, as an additional tool for the tailings classification.

Structural effects may also occur due to desiccation which can impart an apparent over consolidation of the tailings.

3. TAILINGS TECHNOLOGIES

3.1. INTRODUCTION

In most cases, tailings are produced from a flotation process used for minerals separation. The tailings slurry, which is the remaining waste following the extraction of the minerals, exits the processing plant at slurry concentrations typically ranging from 15% to 50% solids concentration.

The tailings slurry is typically discharged at a tailings dam using subaerial or subaqueous deposition methods, which are referred as conventional slurry disposal. Over the last 20 years, the use of tailings dewatering, separation and segregation technologies have been further developed and are currently in wide use. Technologies have also been developed to modify the geochemical characteristics of the tailings (e.g., removal of pyrite or cyanide).

This section describes the various technologies used to produce and manage tailings and how these technologies support the safe containment of tailings and the design of containing dams/embankments. The range of technologies includes equipment, tailings segregation, and design methods. The technologies for control of the water component of tailings slurry range from the historical use of spigotting towards the continuum of reducing the water content with cyclone, thickener and filtration equipment. Segregation of tailings ranges from the conventional use of cyclones, to the application of mill processing alternatives, to the separation of tailings based on geochemical properties. The evolution and application of technologies is evolving in response to objectives to reduce the water losses and improve the chemical characteristics (reduce the potential environmental impact). In addition, reducing the amount of water stored in the TSF reduces the consequences of a tailings dam failure.

The technologies described in this Bulletin may be used independently or combined, and the objective of this section is to describe the basis of each technology. The application of the technologies may then be considered and applied appropriately to the design of a tailings dam, as further considered in Section 4 of this Bulletin.

3.2. SPIGOTTING

Spigotting describes the discharge of tailings from single or multiple locations from the slurry distribution pipeline, which is placed along the dam crest and/or around the perimeter of the impoundment. The size and distance between the spigots are designed depending on the tailings behaviour, solids concentration, flow rate, and desired beach configuration and decant pond location. Special considerations are also required in cold climates to avoid freezing of tailings and water/ice entrapment.

Design of the spigots is particularly important for the construction of upstream tailings dams, where segregation of the tailings slurry along the beach is required to develop a well-drained, well-consolidated zone close to the outer dam slope. The number and size of operational spigots is controlled to ensure that the flow velocity of the slurry on the beach is low enough to allow the heavier (coarser) particles to settle out close to the point of deposition, while the finer particles are carried further out onto the beach, i.e., to achieve tailings segregation. Deposition of slurry with lower solids concentration e.g., <50% solids concentration, is preferred to encourage tailings segregation. Slurries with high solids concentration may form Non-Newtonian flow and show limited segregation.

The beach that develops is concave in profile, with steeper slopes near the point of deposition and flattening out with distance from the point of discharge. The steep beach slopes close to the point of deposition—created by spigotting—create flood freeboard, particularly on smaller tailings dams, where beach length is limited.

Figures 3.1 shows an example of spigots at upstream tailing dams that are designed to promote tailing segregation and beach development.

Fig. 3.1
Spigotting via apertures in the distribution pipe (McLeod and Bjelkevik 2017)

Fig. 3.2
Single point spigot with floating device in a fine tailings impoundment (photo courtesy of D.Grant Stuart)

The selection of the spigot diameter should consider the flow velocity on the beach to avoid formation of channels, which wash away previously deposited materials. Limiting velocity of the discharge is generally considered to be between 0.5 m/s and 1 m/s. The spigot spacing should be close enough to create a uniform outer beach zone without mounding between deposition points, as this could result in ponding and formation of lenses of fine tailings in the coarser outer beach zone. Spigot spacing and number of operational spigots can be manipulated to produce specific layer thicknesses for a given cycle time. The use of more operational spigots results in locally steeper beach slopes than the use of fewer, large diameter spigots that deposit a high energy stream of slurry at wider-spaced deposition points. Spray bar deposition is a variation of spigot deposition. Spray bars are a refinement of spigot deposition, which make use of closely spaced spigots to spray the slurry onto the head of the beach and dissipate energy, allowing rapid settling-out of the coarser particles and segregation of the tailings along the beach. The use of spray bars facilitates the development of uniform beach and reduces the risk of erosion of the beach.

Open-end deposition is discharge from the end of one or a few tailings distribution pipes. This method is often practiced when the development of a beach is not critical to the design of the dam, such as in centerline or downstream construction methods. It is also applied in the winter in cold climates where the larger, concentrated flow reduces the risk of freezing the tailings on the beach. In such cases, spigotting is practiced during the warmer months from the dam to develop a beach and sufficient freeboard, and open-end discharge is practiced during the colder months in an area of deeper water depth.

3.3. CYCLONING

The purpose of the cycloning is to separate the coarse particles from the fine particles in the tailings slurry. The coarse portion (sand) is commonly used for embankment construction. In some cases, the sand is used for sand stacking in a separate facility, or for mine backfill. Cycloning can also be used to “wash” the slurry and remove chemicals as part of the processing.

Cycloning of tailings was developed in the 1960s for the large-tonnage porphyry copper mines and continues to be a major component of tailings dams. Cyclone sand is an excellent embankment construction material and, due to its low fines content, it usually has high hydraulic conductivity and is typically maintained in an unsaturated state. Cyclones work on the principle of centrifugal action—tailings feed is delivered to the vortex finder and the coarser particles are directed to the spigot at the base of the cyclone and the finer particles overflow from the top (Figure 3.3). Cyclones come in a variety of shapes and sizes and can be operated singly or in banks of numerous cyclones. Cyclone selection depends on the tailings type, site conditions and the available suppliers and types of cyclones.

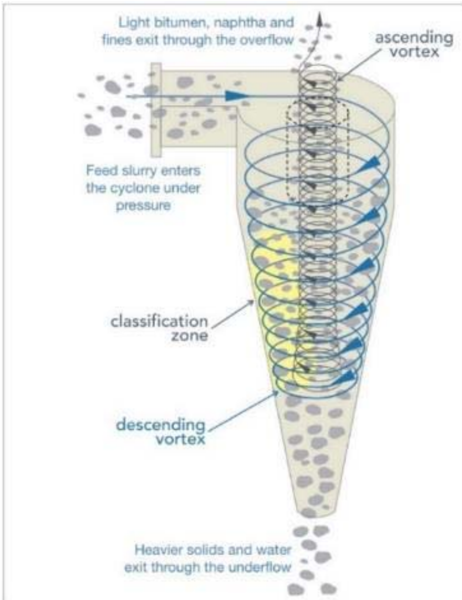


Fig. 3.3
Schematic of hydraulic cyclone (Cyclone Apex. [n.d.])

Cyclones are designed to produce sand with specific characteristics, the most common of which is the percent particles smaller than 63 μm to75 μm in the separated sand portion, although recent works suggests that the 41 μm size may be more representative of cyclone performance. Typically, smaller diameter cyclones produce a more distinct split between sands and silts, although there is a practical trade-off between the number and size of cyclones. The specific requirements for the sand vary from project to project, depending on the site conditions, drainage, density/strength requirements, and sand placement method. The feed slurry concentration should typically be less than 50% as the cyclone is more efficient at lower percent solids feed. The design of the cyclone system depends upon the whole tailings characteristics, percent solids of the tailings slurry feed, and the quantity of sand required for building the embankment ahead of filling the impoundment. The required sand quantity is usually expressed in terms of percent underflow recovery (percent sand of the total tailing subjected to cycloning). In some cases, where the tailings dam has a high efficiency ratio (volume of the impoundment/volume of the embankment), and/or the tailings stream is coarse, only a fraction of the total tailings stream may need to be cycloned to produce sufficient underflow sand for construction of the embankment.

The application of cyclones for dam construction is influenced by the requirements to assure drainage and/or to allow compaction of the tailings for static and seismic stability. Cyclone sand dams have been, and continue to be, used extensively in the large-tonnage copper porphyry deposits worldwide. The selection of the cyclone system is influenced by factors including the following:

- Type of tailings: The efficiency of the cyclone is influenced by the clay fraction of the tailings that may be associated with, for example, altered rock tailings. In this case the use of cyclo-wash cyclones, which introduce a pressurized water flow into the cyclone to improve efficiency, could be required. Multi stage cycloning is also used to achieve the desired gradation. Well-graded tailings are more amenable to cycloning, and it is generally not practicable to cyclone finer tailings.
- Hydraulic conductivity: The hydraulic conductivity is directly influenced by the percentage of fines in the cyclone underflow, which is related to the % recovery of sand from the cyclone. A lower sand recovery can achieve a more permeable sand, however, this needs to be balanced against the construction material requirements for the dam. The specification of the % fines in the cyclone underflow vary up to 20% fines, although higher allowable fines content has been used in coarse tailings. Fines contents of < 15% are typically required if the sand is to be compacted, or if timely drainage of the sand is required.
- Fines content: A lower fines content may be more efficiently achieved with the use of two-stage cycloning. This may also provide an opportunity for having the first-stage cyclone station located off the dam, with the first-stage underflow then diluted and pumped/piped to second-stage cyclones, which could be located on the dam.

- Ore and grinding variations: Variations in the consistency of the grinding circuit, or in the variability in the clay content or gradation of the tailings, decreases the efficiency of the cyclone system and may require a more robust system to accommodate the variability.
- Mechanical and operational simplicity: Cyclone systems need to consider the operational flexibility associated with operating and moving cyclones, transporting, and, if required, compacting the underflow slurry. Additionally, labour and maintenance aspects, and cost, are important.

Numerous variations of cyclone systems have been applied worldwide and continue to evolve to optimize performance. Examples of two different systems used for centerline dams are shown on Figure 3.4 and Figure 3.5. The placement of cyclone underflow in the downstream slope of the dam has been carried out, for example, with the following methods:

- Direct discharge of the underflow onto the dam face without mechanical distribution or compaction. At high dam heights, this method may require mechanical distribution, as the slope of the tailings increases as the dam height increases. Underflow slopes typically range from 4H:1V for low dams up to 2H:1V for higher dams.
- Discharge of the underflow into “cells” located on the downstream slope of the dam. Tailings are compacted with dozers or compactors, and excess water is decanted towards the toe of the dam and recycled.
- Discharge onto the face of the downstream slope with both gravity and mechanical distribution and compaction with dozers, rollers or farm (rubber tired) equipment.

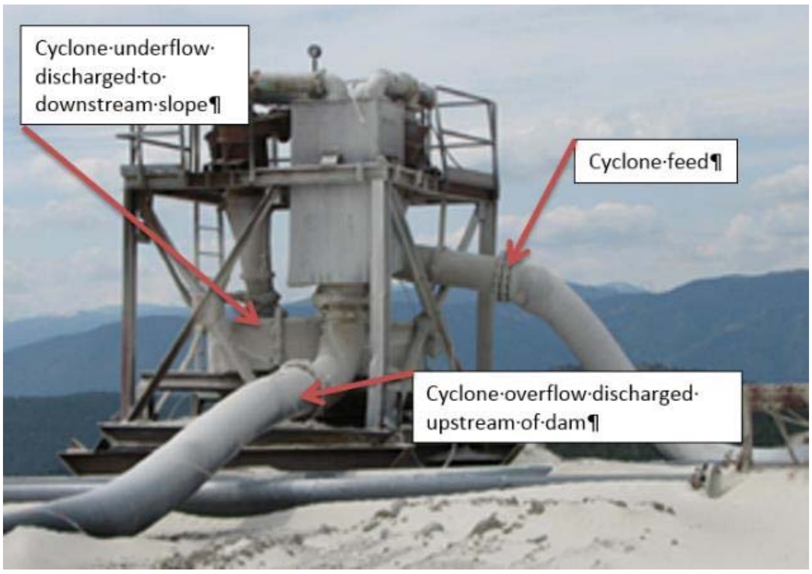


Fig. 3.4
Secondary stage cyclones located on moveable skids on a dam crest and cyclone sand compacted in cells on the downstream slope (McLeod and Bjelkevik 2017)

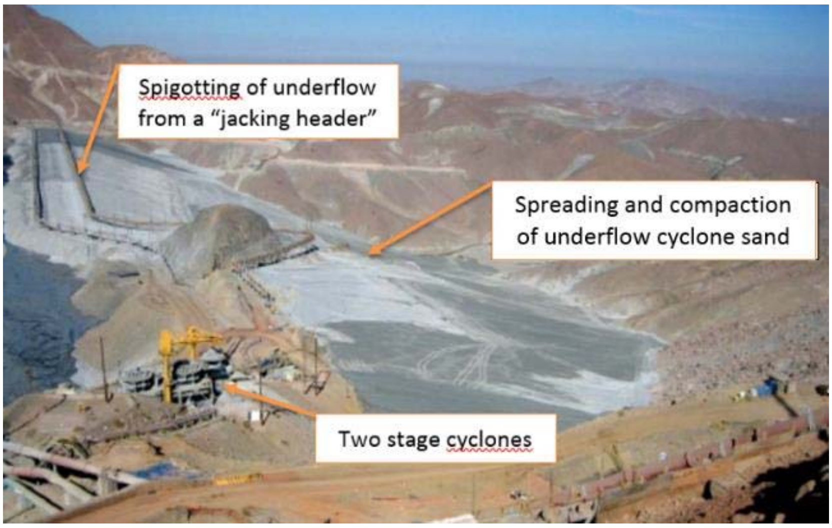


Fig. 3.5
Example of off dam cycloning, spigot distribution on dam and downslope spreading and compaction (photo courtesy of, T.Alexieva)

Cyclone underflow used for upstream dam building should be free-draining to ensure that adequate consolidation occurs before the next lift is placed on it. Typically, a dam constructed with cyclone underflow should be about 100 times more permeable than the fine beach material. Hydraulically placed cyclone underflow could be stacked into a self-building heap that may not require any further material handling or compaction once it has drained. Typical cyclone underflow mounds are shown on Figure 3.6.

Fig. 3.6
Cyclone underflow – upstream dam construction (photo courtesy of, D.Grant Stuart)

Compaction densities achieved for cyclone tailings often exceed 100% standard proctor density, partly due to effects of downward seepage gradients. Where seepage gradients do not exist, such as the base of a dam at the start of construction, placement of cyclone sand as compacted earth fill may be required. Sand should typically be compacted where it may be below the water table and potentially liquefiable. Sand above the water table is typically 50% saturated and not prone to liquefaction.

3.4. THICKENING

3.4.1. Introduction to Thickening

Thickening has been used to improve water recovery from tailings streams since the mid 1990s. Thickening involves the recovery of a portion of the process water as overflow from the thickener for recycling through the plant, with the thickened underflow tailings reporting to the TSF.

The thickening process accelerates settling of the tailings solids with the use of large-diameter steel tanks. The rate of settling and the underflow density achieved is dependent on the equipment, flocculant selections, type of tailings and the yield stress achieved in the thickening process. This is illustrated on Figure 3.7 for different tailings types and thickening technologies.

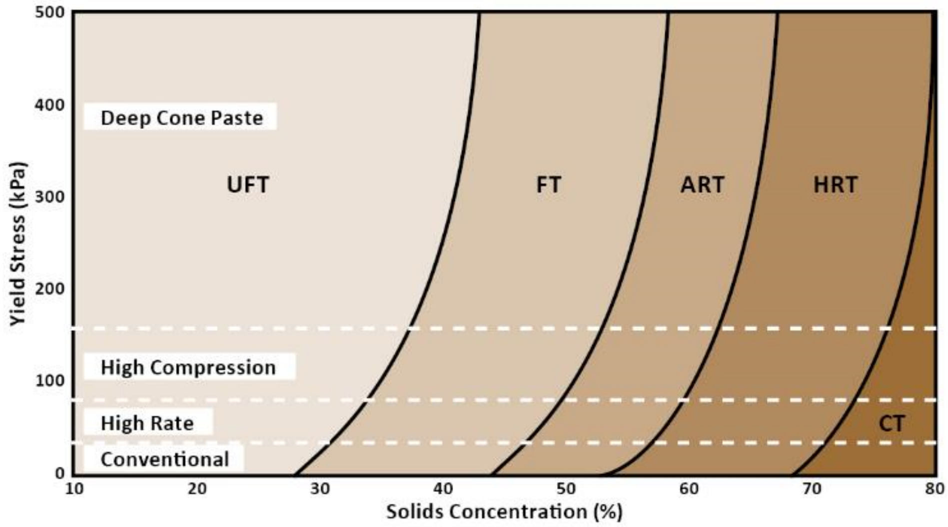


Fig. 3.7
Yield stress ranges versus solids concentration (%) for tailings types and thickener technologies

The density of un-thickened tailing slurry can vary significantly depending on the type of ore and the processing methods. For most metal mines, the density of the processed tailings is typically on the order of 20% to 30% solids concentration, although thickening the tailings slurry to 50% immediately after exiting the processing plant, using conventional thickeners, has become a common practice over the last few decades. The increase in the tailings density depends, to a large extent, on the tailings characteristics: finer tailings with high plasticity are more difficult to thicken than coarser, non-plastic tailings.

Over the last couple of decades, a range of new thickeners have become available and the thickening technology has improved. High rate, high compression, high density and paste thickeners may achieve solid concentrations typically between 55% and 70%. A photo of thickened tailings discharge is shown on Figure 3.8.

Fig. 3.8
Photo of thickened tailings disposal (photo courtesy of, A.Bjelkevik)

The thickening process increases the water recovered in the process plant, versus the water to be managed and recovered in the TSF. Figure 3.9 illustrates the relative volume of water that is recovered from the process plant from various levels of thickening, and that water which is managed in the TSF.

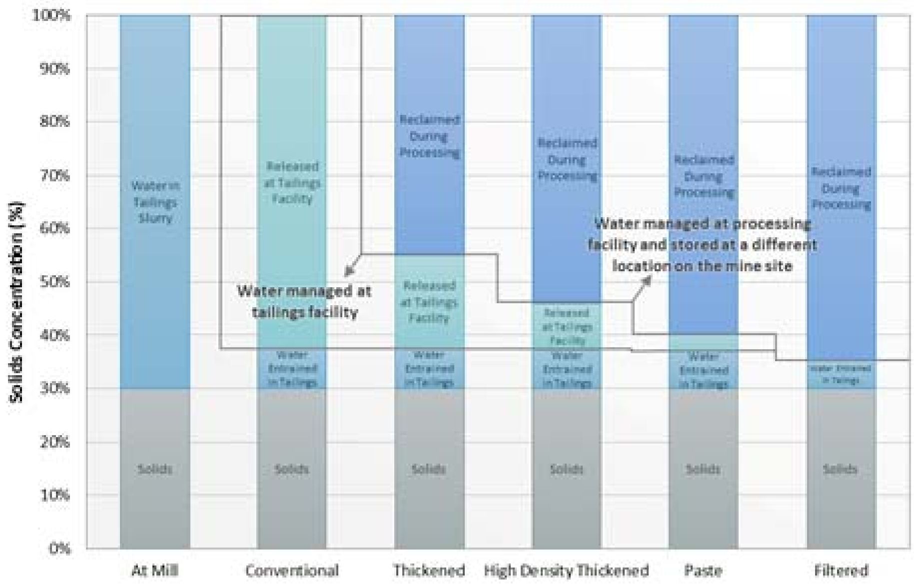


Fig. 3.9
Comparison of water recovery for tailings dewatering technologies (Klohn Crippen Berger 2017)

Thickening of tailings has some advantages that broadly include the following:

- Water recovery is increased at the process plant, which reduces the pumping requirement to the TSF, as well as the pumping requirements for transporting reclaim water back to the process plant.
- In desert environments, where water loss is an important consideration, thickening in the process plant reduces the requirements for minimizing the evaporation losses that occur in the TSF.
- The volume of water stored in the TSF can be smaller due to a lower time required for settling of tailings solids.
- Beach slopes can be slightly steeper, particularly over short distances (e.g., less than 300 m (see Figure 2.15)), which provides opportunities for storage of tailings above the process water pond elevation or, in the case of central discharge ponds, allows for a lower retaining dam height.
- If the tailings are thickened to a density where they become non-segregating (or have reduced segregation), the tailings mass will have a more uniform hydraulic conductivity, which can be beneficial for seepage control.

However, the incremental benefit of the various stages of thickening need to be carefully considered for each site, as there are also negative factors for thickening that may be apparent and could include:

- Tailings naturally consolidate to a paste tailings density within days after deposition in the TSF and continue to consolidate with time to higher densities. Accordingly, the cost of thickening and energy consumption may not offset the benefit.
- The residence time required for attenuation of metals and metalloids may decrease mill efficiency or require additional fresh water supply.
- The requirement for additional water storage facilities for both guarantee of process supply and for flood management.
- The incremental benefits of thickening versus high density thickening or paste may be diminished in wet climates where safe management of rainfall runoff may require substantial water control structures, regardless of the degree of tailings thickening.

3.4.2. Thickening Process

The thickening process is often described as a transition between three zones:

1. Free Settling – Where the particle spacing is sufficient to allow the particles to settle independently of each other.
2. Hindered Settling – Where the particles have become concentrated enough that they begin to interact and settle at a rate that is a function of the solids concentration.
3. Compression or Compaction Zone – Where the particles are in full contact with adjacent particles and are supported by the particles below them and loaded by the particles and fluid above them.

Figure 3.10 presents these three zones, as encountered in an ultra-high rate thickener, moving downward through the thickener, from the inlet to the underflow outlet. The same principles apply to other types of thickeners, although the geometry and mechanical systems vary.

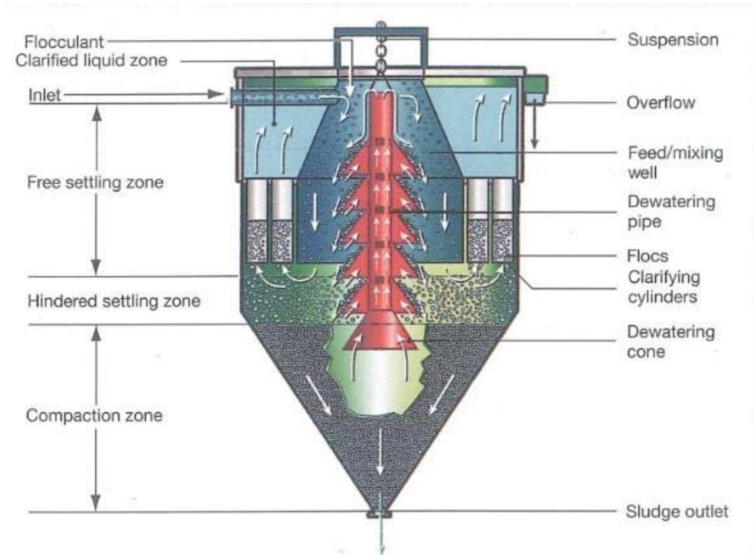


Fig. 3.10
Ultra-high rate thickener schematic –displaying the three thickening zones (EIMCO E-CAT)

Thickeners operate by maintaining a higher settling velocity for the solids within the free settling zone than the upward velocity of the supernatant fluid that is released by the settling solids. If the upward velocity, termed the “rise rate”, is higher, solids are carried up and out of the thickener. After moving through the settling zone (free and hindered zones), the solids reach the compression zone, where their downward movement is constrained by the particles below them and they are loaded by the particles above them.

The residence time, which varies from minutes for conventional thickeners to several hours for paste thickeners, represents the amount of time that the solids spend within the thickener bed—a term commonly used to describe the portion of the thickener where solids are in the compression phase. Compression-zone sizing is often the governing design criteria for ultra high-rate and ultra high-density thickeners, and typically does not play a role in the design of conventional and high-rate thickeners.

The prediction of the thickener underflow density and the rheology of the underflow is typically made by pilot scale tests and consulting a database of test results from similar equipment which processed similar tailings with similar flocculant doses. The use of the database approach to prediction is especially important for ultra high-density thickeners, which have a more limited, historical database and theoretical methodology than conventional, or high-rate thickeners. Laboratory and pilot scale tests typically indicate the maximum achievable solids concentrations, as opposed to average values that are more applicable in practice.

3.4.3. Thickener Designs

The design of thickeners has evolved over time to become more efficient and cost-effective. This evolution has been significantly tied to the evolution of flocculation technology, which plays an integral role in thickening. Figure 3.11 resents a schematic of the evolution of thickener technology. Briefly, thickener design has evolved from units with low height-to-diameter ratios and no flocculant addition—which produce underflow with relatively low solids contents—to units with high height-to-diameter ratios, which utilize synthetic flocculants to increase the settling rates and produce underflow with significantly higher solids contents. Consequently, there are now a wide variety of thickener designs available from different manufacturers and project-specific applications.

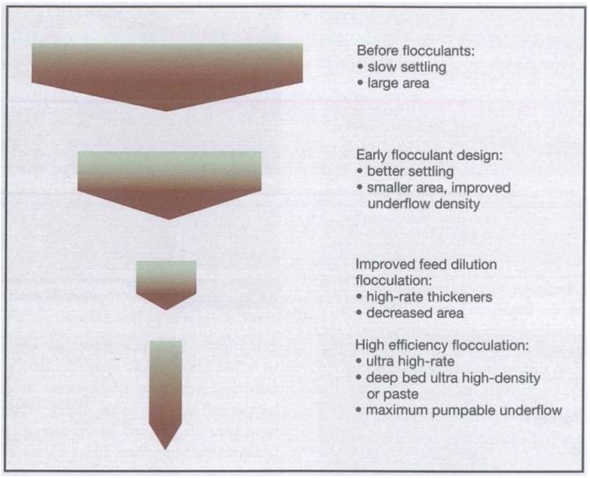


Fig. 3.11
Schematic illustrating thickener evolution (Bedell 2006; Jewell and Fourie 2006)

The terminology used to describe thickeners often varies based on the thickener equipment supplier and region of use. However, thickeners are typically classified into four categories, discussed in the following sections.

Conventional Thickeners

The term "conventional thickener" encompasses thickeners used in the mining industry since the 1960s and includes many of the thickeners in use today. Conventional thickeners typically have a low depth-to-diameter ratio and generally rely on the settling characteristics of the solids, aided by large area and low rates of rise to form a settled solids bed on the floor of the thickener. The use of conventional thickeners typically increases the solids concentration of a slurry by about 20% to 30%, depending on the characteristics of the tailings. The diameters of conventional thickeners can vary up to 100 m or more. An example of a conventional caisson thickener is shown on Figure 3.12.

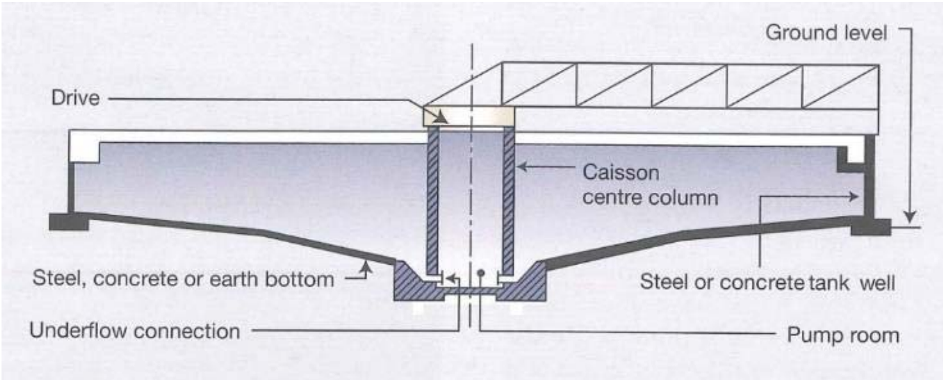


Fig. 3.12
Caisson thickener schematic

High Rate or High Capacity Thickeners

High Rate thickeners were first developed in the 1960s and have a higher depth-to-diameter ratio than conventional thickeners. They operate in an environment of higher throughput per unit area and their operation usually includes the addition of flocculants to develop a solids bed in conditions of higher rate of rise in the thickener. Diameters of high rate thickeners are typically between 20 m and 50 m. Depending on the type of tailings, solid concentrations of up to 65% (hard rock tailings) may be achieved. An example of a high-rate thickener is shown on Figure 3.13.

Fig. 3.13
High-rate thickener (Image reference, Outotec^{TM}.com, 2019)

High Compression or High-Density Thickeners

High Compression, High Density and/or Ultra High-Rate thickeners represent a further advance in thickener technology. They typically have smaller areas and higher depth to area ratios than conventional or high-rate thickeners and utilize specialized internal components to achieve rapid removal of water from the feed and high-density underflow. Ultra high-rate thickeners utilize a specially designed feed well, dilution systems, and specialty internal components such as dewatering cones and clarifying cylinders to enhance solid-liquid separation. An important distinction is that high compression and paste thickeners have significant bed depths and hence residence time, allowing for some consolidation in the bed. The diameter of the unit may be limited by the available rake torque. As higher capacity drives become available, the diameters of these units will increase.

Deep Cone (Paste) Thickeners

Ultra High-density thickeners are also known as Ultra High-Density, Deep Cone or Paste Thickeners. Ultra high-density thickeners use some of the features of the previously described thickener types, in combination with advanced controls, to achieve underflow with higher solids contents. The features include a specialized feed well; dilution systems; a deep tank with a high depth-to-area ratio for higher compression and long residence times; specially designed rakes; and advanced instrumentation to control flocculant dosage, solids inventory and underflow density. Instrumentation and quick response to changes in underflow properties is extremely important for ultra high-density thickeners, as they operate in a portion of the tailings continuum where the yield stress can change significantly with small variations in solids content. Figure 3.14 presents a photograph of an ultra high-density thickener.

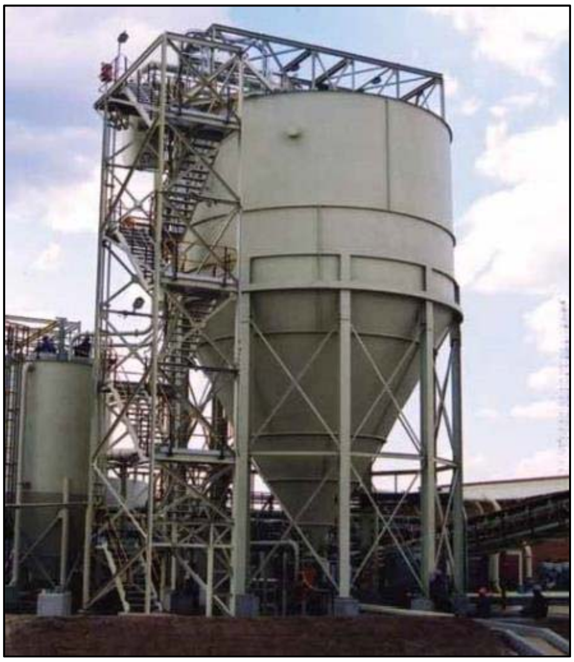


Fig. 3.14
Ultra high rate thickener (deep cone paste thickener) (EIMCO E-CM™ – Jewell and Fourie 2015)

One definition of paste tailings state is the density at which the tailings would have completed its initial settling, with little remaining bleed water. This density state is typical to what is represented by the jar settling tests as shown on Figure 2.6. It is also described as the density at which a positive displacement pump is required to transport, typically represented by tailings with a yield stress of greater than 200 kPa. Achieving a paste density state may be achieved by mixing thickened tailings with filtered tailings.

The application of deep cone thickeners to surface tailings storage facilities are challenged by the following:

- Difficulty achieving the desired density consistently. Actual performance results typically produce an underflow density of 62% to 67% solids concentration for hard rock tailings.
- Higher capital and operating costs than other thickener processes (typically twice the cost of high rate thickening).
- Higher mechanical and operating complexity and reagent cost.

- When a higher density is achieved, it requires positive displacement pumps and high-pressure pipelines.
- The paste forms a steep slope (up to 6%) over a short distance (100 m), which requires continual moving of the discharge point to be able to spread the tailings over a larger area to achieve the storage requirements. However, overall slopes are typically less than 3%.

The authors are not aware of any successful application of paste tailings, and most reported paste projects achieve solids concentrations more representative of thickened tailings. Application of Ultra High-Density thickening has been carried out for various scale operations, however their success (i.e., achieving high solids concentrations) has, to date (circa 2018), been variable and reported solids concentrations appear to be in the range of up to 65% for hard rock tailings. The greatest achievements of paste and ultra-high density thickened tailings to date have been in arid climates where improved water recovery is the driving factor, with reduction of water reclaim and management facilities as a secondary benefit.

3.5. FILTERING

3.5.1. Filtering Process

Filtering of tailings has been practiced since the 1970s. However, due to the significant capital costs of the filtering equipment and the operational costs, (maintenance and power consumption), filtering was not feasible for many operations as it did not provide an added benefit of improved metals or chemicals recovery, or lower capital cost. With the improvement in the efficiency of the filtering equipment and the focus on reduced water consumption, together with the reduced risks of physical stability and potential environmental risks, interest in tailings filtering has significantly increased in recent years.

While there are a variety of filter types available, at a basic level, all filters operate under the same general concept. Filters use a porous surface to retain the solid particles from the feed (which are known as the filter cake) along the porous surface, while driving the liquid portion of the feed through the porous surface. The remaining liquid within the cake is typically described in terms of moisture content.

Filters used for tailings dewatering can be categorized into two primary types: vacuum and pressure. Vacuum filters use vacuum pressure to draw moisture from tailings through a filter membrane, while pressure filters squeeze the tailings between filter membranes. Vacuum filters include drum, disc or horizontal belt filters, while pressure filters include plate filters or pressure belt filters. Vacuum belt filters and horizontal plate filters are considered most suitable for the tonnages often required by mining projects and are used in most filtered tailings operations.

As filters are much less efficient at removing excess water than thickeners, thickeners are typically used to dewater the tailings to approximately 60% solids concentration before filtration. Filtration further dewaters the tailings, typically to 80% to 88%, depending on the filtration processes and cycle times.

How readily tailings can be filtered is most influenced by the type of tailings (finer tailings are more difficult to dewater) and plasticity (higher plasticity tailings are more difficult to dewater). High plasticity tailings may also result in a sticky filter cake, which may be difficult to clean from the filter medium and to handle after filtration.

Redundancy is an important consideration in the selection of filters. Filter operations will typically have multiple filter units to allow for the performance of routine maintenance on individual units while maintaining the design throughput.

Filtering of the tailings results in a reduction in the water losses associated with tailings disposal and can achieve higher density of the deposited tailings. The lower water consumption may allow higher production rates in dry areas with limited water availability, and the higher density may result in opportunities to reduce the footprint of the TSF or allow progressive reclamation. In some cases, the filtering process may be used to extract, and reuse chemicals used in the mineral processing, thus reducing both the processing costs and potential environmental impacts.

3.5.2. Filter Types

Vacuum Filters

Vacuum filters operate by using a vacuum to "pull" the liquid portion of the feed through the filter medium and filter cake. Vacuum belt filters offer a lower cost but may not achieve optimum moisture content for compaction, particularly in finer tailings. Their use, therefore, may be limited to dry climates where air drying of the placed tailings can be used to further reduce the moisture content after placement, or in sandy tailings. Vacuum filters are typically operated in a continuous manner and are used for higher throughput requirements. All vacuum filters face elevation constraints, as decreases in the atmospheric pressures at higher altitudes reduces the amount of force available to pull the liquid through the filter medium and filter cake. Typical vacuum filters can be divided into three categories:

- Drum Filters consist of a cylindrical filter drum, which is a horizontally mounted cylinder connected to a motor. The drum face is divided into sections and the face of the drum is covered with a filter medium.

When the drum is operated, vacuum pressure is applied through the vacuum cells and the drum is rotated through a filter tank and a portion of the slurry feed forms a cake on the filter medium.

- Disc Filters operate in a similar manner to drum filters, but with a revised geometry that increases the filtration surface area, thus decreasing the required filter footprint (Figure 3.15).

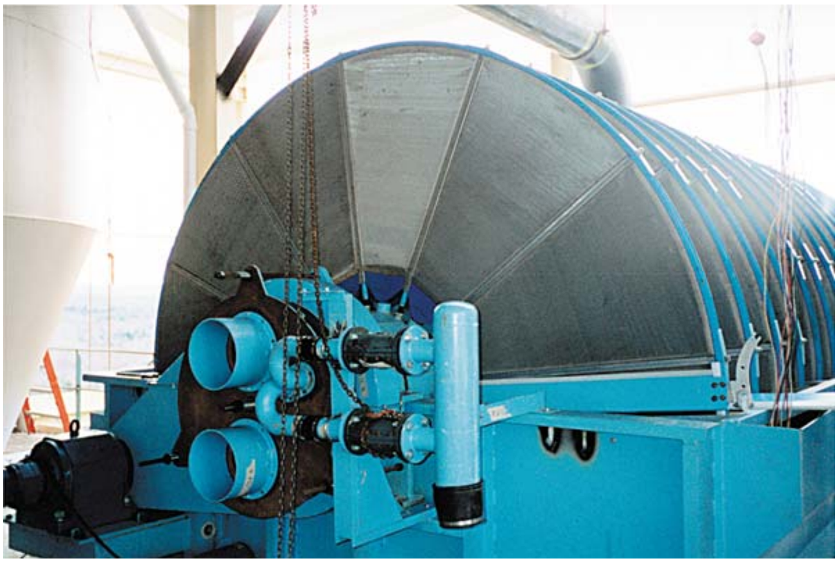


Fig. 3.15
Vacuum disc filter (WesTech [n.d.])

Horizontal Vacuum Belt Filters consist of a perforated, or slotted belt, covered by another belt of a filter medium. The slotted belt runs on top of a lubricated table, or roller conveyor, that includes vacuum ports. A schematic of a typical horizontal vacuum belt filter is shown on Figure 3.16.

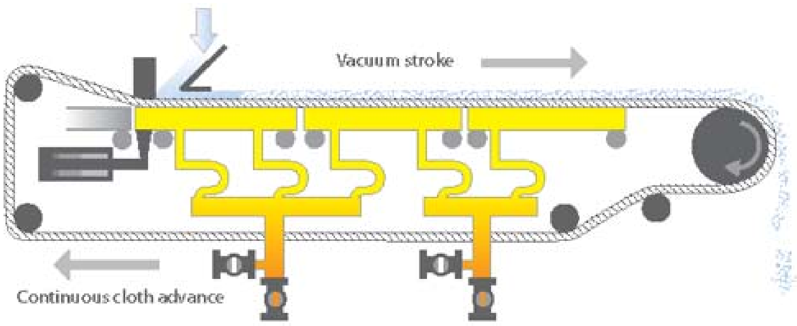


Fig. 3.16
Horizontal vacuum belt filter schematic (OutoTec Larox RTTM) (McLeod and Bjelkevik 2017)

Pressure Filters

Pressure filters use mechanical pressure to "push" the liquid portion of the feed through the filter medium and filter cake. Pressure filters can apply more pressure to achieve moisture contents near the optimum moisture content for efficient compaction, however they are significantly more expensive to operate, and operate in batches rather than as a continuous process. Horizontal plate filters offer the highest capacity for pressure filtration. Typical pressure filters can be divided into three categories:

- Plate and Frame Pressure Filters (also known as horizontal pressure filters, vertical plate filters or chamber pressure filters) consist of a frame and cylinders. Filter plates are installed within the frame, along rails, and covered with filter cloths. Figure 3.17 presents a schematic of a plate and frame pressure filter. To provide solid-liquid separation, the feed material enters the filter chambers (i.e., the space between each filter plate) through feed ports. After the feed material is injected, the filter plates are compressed—typically by a hydraulic cylinder(s). Due to the nature of plate and frame filters, they are "batch operated," producing filtered tailings at the end of each filtration cycle, rather than producing filtered tailings in a continuous manner like many other filter types.

The largest units currently have up to 120 chambers with 2 m x 2 m filter plates (FLSmidth, 2011), and offer capacities up to 8 500 tpd/filter, depending on tailings properties. Larger filter plants are currently under production and increased efficiency and scale of operations could be anticipated to increase in the future.

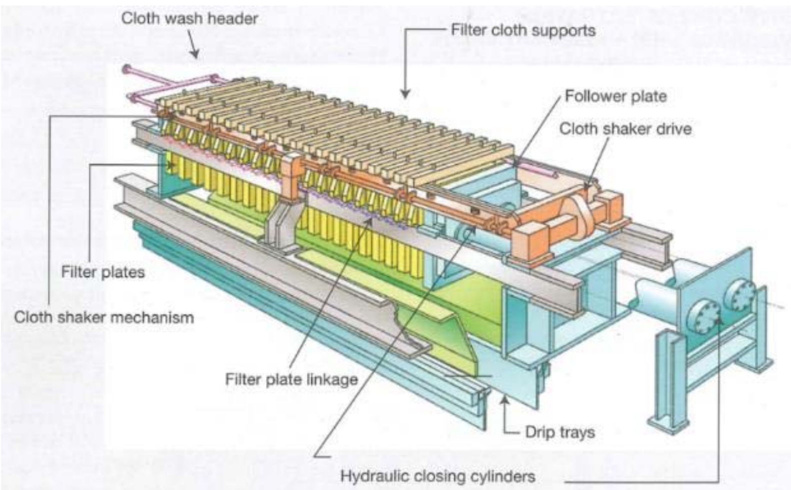


Fig. 3.17
Horizontal plate and frame pressure filter schematic

- Membrane Pressure Filters operate in a similar manner to plate and frame pressure filters, utilizing filter plates and producing filtered tailing in a “batch” manner. However, in membrane pressure filters, compression of the tailings within the chamber is performed by inflating membranes.
- Belt Pressure Filters operate in a similar manner to vacuum belt filters, in that they consist of a continuous belt running along a frame, and pulleys, which use the pressure from an overlying plate to force the feed material against the filter media overlying the belt. These filters may be stacked vertically (termed “tower filters”) to reduce the footprint.

3.6. TAILINGS STREAMS SEPARATION

Typical practice in tailings management has been to combine tailings from various parts of the processing system and discharge a single tailings stream. This is despite some of the tailings components having quite different physical or chemical properties which could allow separate management practices to optimize environmental or economic benefits. It is therefore very important that tailings dam designers consult with the process designer(s) to understand opportunities for optimizing the tailings stream(s) either on physical or geochemical properties.

Separation on Physical Behaviour

Cycloning, as previously discussed, is an example of separation of a tailings stream based on physical behaviour. However, there are cases where separate tailings streams within a plant already have distinctive properties, which may provide an opportunity to manage them separately. For example, it is common for a primary/secondary crushing circuit to generate sandy tailings, which are separated by gravity (dense media separation), with heavier mineral grades sent back to a grinding circuit prior to flotation or other further process. This results in both coarse and fine tailings streams that could be managed as separate materials. Similarly, coal processing results in both coarse and fine rejects, which are commonly treated as separate waste streams. Magnetic separation processes are also used in some mills, producing different waste streams that could be managed separately.

Separation on Geochemical Properties

Sulphide minerals in the tailings can oxidize and lead to ARD with associated environmental concerns. Acid water can then react with other minerals, and although the acid is neutralized, to some extent, by the minerals it reacts, this is normally at the expense of increased metal or salt concentrations. In some cases, the acid generated can be neutralized with precipitation of metals such as aluminum, copper and lead. However, at near-neutral pH, concentrations of toxic components such as zinc, arsenic, nickel, and cadmium, can remain elevated.

In some processing plants, low-sulphide tailings are produced by a gravity circuit or a rougher-flotation circuit, which can comprise a substantial proportion of the total tailings stream and may not be potentially acid generating (non-PAG). In this case, the lower-volume high-sulphide tailings (cleaner circuit) can be managed separately in a saturated containment facility, and the higher-volume rougher tailings would be placed in a conventional storage facility.

Brukard and McCallum (2007) showed how a range of separation processes could be used to remove sulphides from tailings and produce low-sulphide sand suitable for construction use, plus a range of potentially valuable metallic by-products. Processes included simple screening, gravity methods, magnetic separation, and froth flotation. Bois et al. (2005) describe the desulphurization of a tailings sample containing typically 20% sulphide to a low-sulphide NAG/NAF tailings and a high-sulphide PAG/PAF tailings. Cement stabilization tests showed no detrimental effect in using the high-sulphide tailings for underground backfill.

Some of the options for management of the reduced volume of sulphide tailings include:

- Placement underground, where the natural groundwater level will maintain their saturation;
- Placement underground as cemented paste tailings;
- Storage sub–aqueously in a purpose-designed dam, either with a water cover or a “dry” cover designed to maintain saturated, sub-surface conditions;
- In-pit storage, where the water table will saturate the tailings; and
- Potentially compacting tailings to a level where the hydraulic characteristics of the tailings mass retains water, and a high level of saturation can be maintained by infiltration of rainfall.

3.7. INTEGRATED TAILINGS AND WASTE ROCK MANAGEMENT

On larger mining projects, where the ratio of mine waste rock to tailings can be relatively high, there may be opportunities to integrate the storage of tailings with the waste rock. Integration can range from “co-placement”—combining the waste disposal sites to take advantage of waste rock to create a storage facility for tailings (integrated waste landform)— to “co-mingling,” where the tailings and waste rock are combined.

3.7.1. Co-placement

Tailings and coarse waste rock are transported independently and co-placed within the TSF. Examples are waste rock placed into a tailings facility, or waste rock used to create internal berms or retaining walls of a tailings facility.

An integrated waste landform can be formed by buttressing the tailings dam with waste rock and shaping the waste rock to form a “natural” landform. This can result in a conservatively more stable TSF structure than if the waste facilities had been separated. Design of the structure needs to consider the normal issues for design of a conventional tailings dam to ensure that the external support structure is stable, and that materials are zoned to prevent piping of tailings. This type of construction may provide savings in capital and operating costs for perimeter embankment construction and environmental benefits through progressive rehabilitation. Perhaps the greatest, intangible benefit are very conservative factors of safety for embankment stability, which can be higher simply due to the mass of waste surrounding the TSF.

Co-placement of PAG/PAF waste rock into a saturated tailings facility has also been carried out to mitigate the water quality concerns with PAG/PAF waste rock.

3.7.2. Co-mingling

Depending on the porosity (void ratio) of the waste rock, there may be available “void space” to store tailings. This allows potential for “co-mingling,” where tailings are recombined with waste rock to produce a mixed material with strength parameters dominated by the rock material and hydraulic parameters dominated by the tailings. This material will have low hydraulic conductivity, good water retaining parameters, and resistance to oxidation and generation of ARD. According to INAP (2009), layered co-mingling of waste rock and thickened tailings can also limit the acid generation potential. Alkaline tailings can be mixed with PAG/PAF waste rocks (Leduc el al. 2004), or tailings can be amended with alkaline material to increase the chemical stability of co-disposed materials (INAP 2009), recognising the potential increased salinity in seepage water and possible neutral metalliferous leachate.

Co-mingling is becoming common in the coal industry, where coarse and fine washery rejects can be combined and pumped as a mixture or conveyed or trucked to the storage facility. It is, so-far, less common in hard-rock mining due to the practicality of combining and transporting mixed material containing large rock particles, but methods for mixing in cells have been considered.

Renaming of old technologies includes the introduction of eco-tails and paste rock, where high density thickened tailings or filtered tailings are combined with waste rock as part of the processing, and then conveyed to the waste storage facility. Research on mixing of waste rock and tailings continues to be carried out (Wickland et. al, 2006). Caution must be exercised in the assessment of the properties of the mixed materials that considers the strength reduction due to the tailings incorporation and the potential geochemical benefit of reducing oxidation processes.

3.8. OTHER TECHNOLOGIES

3.8.1. Cell Construction to Promote Evaporation

Scheduled placement of tailings into confined cells can provide opportunities for accelerating drainage, consolidation, and desiccation of the tailings. In this application, a thin layer of tailings is discharged into one cell and then deposition moves to the next cell. The first cell is then allowed to drain, consolidate and desiccate, resulting in dense tailings that can be resistant to liquefaction and undrained loading. The methodology, however, is reliant on available space to construct numerous cells, and on having sufficient evaporation rates.

3.8.2. Cell Construction to Minimize Evaporation

Minimizing evaporation losses is a critical component in arid desert climates where water supply can be costly and challenging to obtain. It can be a significant natural resource that should, as far as possible, be preserved. Alternative water sources, such as desalinated seawater, can be used, but are expensive.

The design of a TSF to limit evaporation consists of dividing the TSF into cells, which can be separated with splitter dykes constructed of dried tailings (or waste rock). The cell is sized to store tailings, typically for weeks or months. The objective is to minimize the active wetted tailings beach area, which is the most significant source of evaporation loss. The inactive cells continue to consolidate and desiccate, with decreasing amounts of water expelled to the surface. Typically, a TSF could have 4 to 10 cells depending on the production rates and TSF area. Water recovery with such systems can be equivalent to that recovered in the process plant using high capacity or high rate thickeners.

3.8.3. Mud Farming

Mud Farming is the process of mechanical disturbance, or ploughing, of tailings to break up a forming desiccation crust and to improve surface drainage and desiccation. The objective is to increase the density and strength and to reduce the degree of saturation of tailings to meet stability requirements. Mud farming has been used in the alumina industry and has also been used in dredged spoil and oil sands tailings (Munro and Smirk, 2015). The mud farming technology has the potential to improve the risk profile of upstream tailings dams, without the need for the higher capital cost of centerline or downstream dam construction.

Specialist equipment has been developed to allow access to soft tailings beaches to be able to scroll the surface and promote surface drainage and evaporation. This includes Archimedean screw tractors known as “amphirols”, and amphibious excavators are also used.

Mud farming with amphirols involves:

- Discharging tailings to a defined depth (usually a maximum of 1 m) by filling a cell or paddock.
- Allowing initial surface drainage and consolidation, and the initiation of surface crusting (typically over several days).
- Introduction of the Amphirol to the tailings by tracking or “scrolling” up and down the beach in the direction of the beach slope; this creates swale drains, as shown on Figure 3.18, promoting drainage of decant water and rainwater to the decant pond, allowing improved recovery of water to the process, and exposing a larger surface area to evaporation.
- Periodic removal of the Amphirol to allow drainage and evaporation from the elevated mounds of tailings between the scroll tracks, followed by reintroduction, as the surface becomes dry.
- Introduction of other equipment, such as swamp dozers, once the tailings are sufficiently farmed to support this equipment; and
- Final compaction to the required density.

Fig. 3.18
Amphirol operating on a tailings beach showing swale drains being formed
(photo courtesy of, D. Brett)

3.8.4. Technology Developments

Development and improvement of technology is ongoing, and the continued pursuit of technologies that dewater tailings, or produce a less hazardous tailings, is important. Some of the following technologies are historic and their exploration is continuing; others are new technologies under assessment.

- Geotextile Tube – Geotextile tubes filled with feed material can be used to perform solid-liquid separation. When used for tailings, the filled "tubes" can be stacked to form a "dry" landform. Geotextile tubes have also been used for dewatering of sludges from waste and mine water treatment, and for coal wash waste.
- Centrifuge – Centrifuges use the force from the rapid rotation of a cylindrical bowl, or a central helical shaft, to force the feed material against a filter medium and provide solid-liquid separation. There are a variety of centrifuge types, but it appears that decanters and screen bowls may be the most common in the mining industry. They are only applicable to very low throughput. It also appears that centrifuges have only been adopted for tailings with high ultra-fine particle contents and very slow settling rates, such as phosphate tailings, coal wash slurries, and fluid mature fine tailings (MFT) produced in the oil sands industry. Centrifuges typically only remove a relatively small portion of the liquid from the feed material, as compared to other filter types.
- Tube Press – Tube presses can operate at high pressures and provide a high degree of liquid-solid separation. A tube press consists of two concentric cylinders and a bladder, which is operated hydraulically. The bladder is filled, reducing the volume of the annulus, and forcing the feed material against the filter medium of the candle. This process is "batch operated" and does not produce a continuous product.
- Screw Press – This device consists of a gear box and motor connected to a screw (helical)- shaped central shaft, surrounded by a cylindrical perforated screen.

4. TAILINGS DAM DESIGN PRACTICES

4.1. INTRODUCTION

The state of practice of tailings dam design continues to evolve. Its foundation is sound geotechnical engineering that incorporates environmental protection, with the goal to transition the tailings facility into a sustainable landform, or a suitable land use facility. There are a multitude of tailings dam designs in use today that have been developed in response to site-specific conditions and are often modifications of historical designs. New technologies, increased environmental requirements, and dam safety standards continue to drive the evolution of tailings dam design.

The purpose of this section of the Bulletin is to illustrate the range of tailings dam designs that are in use today and to discuss key technical aspects that control dam safety. The selection of a design is significantly influenced by the available sites and the site condition, which may drive requirements, for example, for seepage control, seismic protection, water recovery, dust control, climate, etc., or may provide opportunities for increased robustness in the design.

Tailings dams provide an opportunity to take advantage of incorporating the tailings into the design to reduce hydraulic gradients and the risk of piping, and to optimize the structural zone of the dam. These considerations provide a safety advantage, and potentially a cost advantage, for tailings dams as compared to water dams. Sustainable design practices for tailings dams are described in the recent ICOLD Bulletin 139. The objectives of sustainable design are, upon completion of mining, resilient structures that are physically, chemically, ecologically and socially stable. In most cases, the dam and the impoundment are integrally connected. All components of the TSF work together and a change in one of the components usually triggers changes throughout the system.

Tailings dams have historically been categorized into three general classes (upstream, centreline and downstream), which are still relevant today. Alternative technologies, such as filtered and thickened tailings, still require a stable structural zone, which may also comprise an upstream, centreline or downstream design. In general, upstream and centreline dams are more challenging for fine and ultrafine tailings due to lower tailings strength.

4.2. STARTER DAMS

Tailings storage occurs over the life of the mine, which can vary from as little as five years to more than 100 years. Consequently, the general practice is to construct a "starter dam" and then either raise the dam continually, or in staged construction periods. The starter dam is often sized to store approximately two years of tailings and, in some cases, the operational start-up water volume. This provides time for the process plant to become fully operational and allows planning and construction time for the first raise. Other considerations for the sizing and design of the starter dam include:

- topography constraints;
- staging requirements for mobilization of construction equipment;
- climate (schedule windows such as limitations on winter or wet season construction);
- rate of rise for upstream dams;
- time to get cyclones running and form upstream beach, and availability of sand; and
- flood routing and requirements for water storage for start-up and for flood control.

The starter dam design section may be like a conventional water dam section and typical sections are shown on Figure 4.1. In addition to the conventional water dam design considerations, the use of the starter dam to store tailings provides opportunities to reduce the risk of the structure with the following considerations:

- Geomembrane/tailings liner systems have been shown to have extremely low leakage rates, on the order of 0.001 L/s/km^2 (Rowe et al. 2016). Nonetheless, geomembrane lined dams should consider a bedding that is filter compatible with the tailings, in case there are defects in the liner.
- Centreline core starter dams that include a rockfill zone upstream of the core is not a recommended practice for tailings dams. The upstream rockfill zones will become fully saturated with the full hydraulic head of the impoundment, resulting in maximum hydraulic gradients across the core over the life of the dam. Instead, the practice of placing tailings adjacent to the core zone is preferred, as the tailings reduce the hydraulic gradients through the core in the event of hydraulic fracturing, and the tailings may also act as a crack stopper.

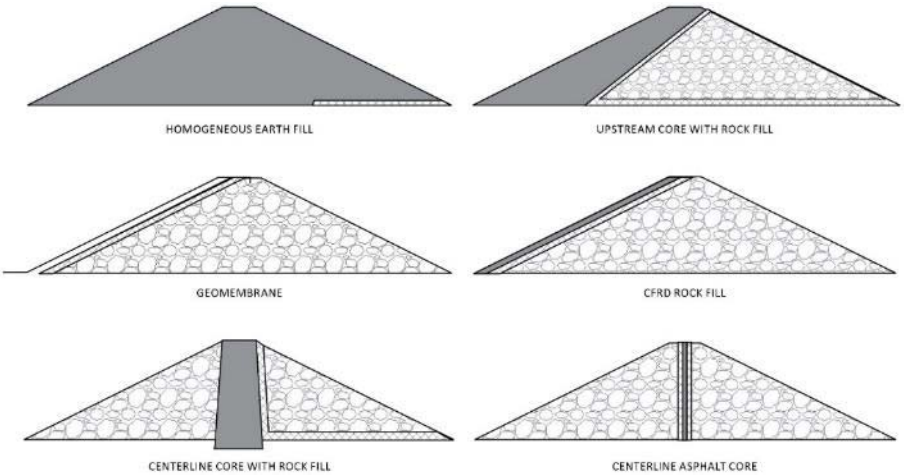


Fig. 4.1
Typical examples of starter dam and downstream dam cross sections

4.3. DOWNSTREAM DAMS

Downstream construction is the method in which the structural portion of the tailings dam is relatively independent of the tailings and raising of the dam takes place by filling on the downstream side. This allows the dam to be engineered by a conventional construction process and allows incorporation of water dam features, such as storage of surplus water against the dam.

A conventional low hydraulic conductivity core and filters are typically incorporated in the design. If the embankment is to be constructed in stages, then a sloping core may be used to facilitate future raises. Raising of the starter dam with a downstream dam section may continue with the same design as the starter dam, or could include conversion to, for example, a pervious cyclone sand or rockfill structure. Considerations relating to raising the dam include:

- If seepage is not a significant concern, the low hydraulic conductivity core or liner may be eliminated or modified to allow seepage through the dam.
- If a liner is used to reduce seepage to the foundations and through the dam, then a system of internal drainage may be used to desaturate the tailings over the long term. Recent research on liners (Rowe et al., 2016) suggests that tailings/geomembrane liner systems are more robust than conventionally considered.
- The selection of an appropriate core width should consider the influence of tailings on the risk of hydraulic fracturing, as it is typical to have core widths on tailings dams that are less than on water dams.

- High dams with geomembrane liners need to consider the stresses on the liner as the dam is raised. In some cases, concrete curbs have been used and liners extensively “pinned” to the dam face.

4.4. DESIGN PRACTICES FOR CENTRELINE DAM CONSTRUCTION

Centreline dam construction was introduced in the 1960s and takes advantage of the benefit of tailings to support the upstream slope of the dam, thereby reducing the dam volumes associated with a downstream dam. The centreline dam allows the complete structural zone of the dam to be constructed with conventional equipment, with good quality control and quality assurance of fills, as opposed to an upstream dam.

The dam comprises a vertical extension of the starter dam centreline, with the downstream zones consisting of conventional dam construction materials or cyclone sand. The requirement for a low hydraulic conductivity core is usually determined by the potential environmental or engineering criteria to minimize seepage. Typical examples of centreline dams are shown on Figure 4.2.

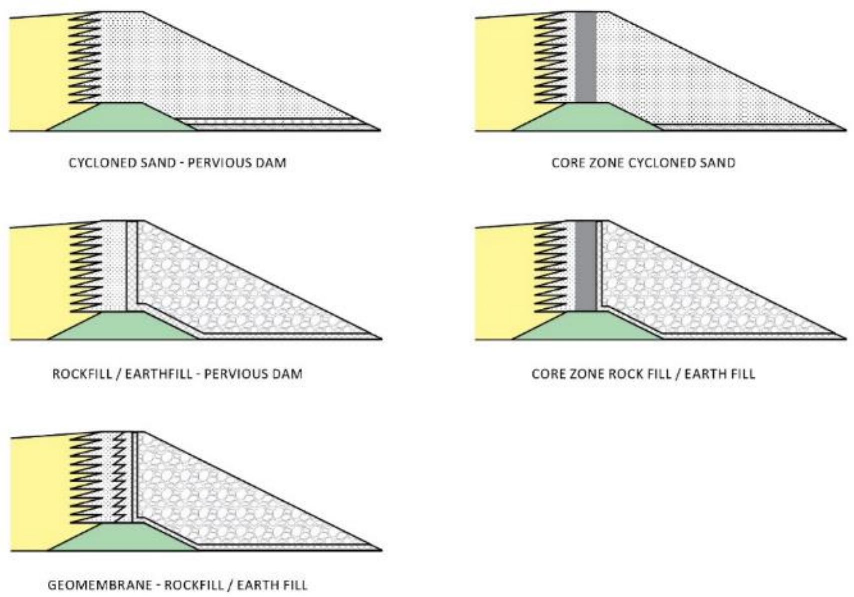


Fig. 4.2
Typical design sections for centreline dams

The stability of the upstream slope is dependent upon the strength of the impounded tailings, which form part of the upstream section. Liquefaction of the impounded tailings under cyclic loading may lead to localized upstream slope failures in the upper section of the dam. Provided these potential failures do not compromise the ability of the dam to contain tailings, they may be an accepted risk and repaired after the event.

The upstream support for the dam relies on a portion of engineered fill that is partly placed on the impounded tailings, which may consist of some of the following components:

- spigotted tailings or beached cyclone overflow;
- cycloned sand with a higher percentage of fines than typically used for the downstream zone;
- tailings cells in which total tailings is deposited and compacted with a dozer while water and fines are decanted off the end/edge of the cell;
- earth fill borrow material.

The use of rockfill is not recommended as it creates a zone in which high hydraulic heads will persist against the core.

Dams required to contain large volumes of water against the dam, or provide a large freeboard, may require that the centreline geometry be changed to a modified downstream, or downstream geometry.

The low hydraulic conductivity core zone may consist of:

- low hydraulic conductivity soils or bentonite amended soils or tailings;
- a geomembrane placed in a “zig-zag” fashion, ideally with cyclone sand on either side; and
- asphalt core zonation that is typically used in water dam construction.

The downstream zone may consist of cyclone sand as described in Section 3.3 of this Bulletin. Considerations for a cyclone sand dam include:

- An underdrainage system to collect and direct the downward seepage flow from the placed cyclone underflow tailings sand. The cyclone sand, therefore, requires a high enough hydraulic conductivity to promote good drainage.
- The cyclone underflow tailings can be placed in the downstream zone using various methods which have historically included:

    - Direct discharge from the crest of the dam. In this case, tailings are deposited at a natural slope of approximately 4H:1V, although as the dam height increases, the slope also steepens.

- Discharge into long pipes placed down the slope of the dam. The pipes have holes that allow tailings discharge parallel to the dam slope. The pipes are pulled up the slope and relocated to ensure distribution of the sand. The sand can be compacted with dozers, or compactors, running up and down the slope of the dam.
- Discharge from spigots located on the dam crest, with the tailings spread and compacted with mechanical equipment.

- Cyclone underflow is directed, via a pipe, to a cell located on the downstream slope of the dam. The cell is formed by a dozer pushing tailings up to a height of approximately 1 m. Cyclone sand is deposited and compacted with a dozer or a compactor. Surplus water is drained from the cell at a low point and directed towards the toe of the dam.
- In seismic areas, the sand needs to be compacted, unless there is assurance that the cyclone sand will not remain saturated.

Variations of centreline dams includes both modified upstream and modified downstream dams as illustrated on Figure 4.3. The modified downstream method is sometimes used when an allowance for storage of large volumes of flood water is required. The modified upstream method is sometimes used when optimizing an upstream design section. Special consideration for the modified upstream is required for potential settlement and/or cracking of core and filter zones, as these zones are overlying un-compacted tailings.

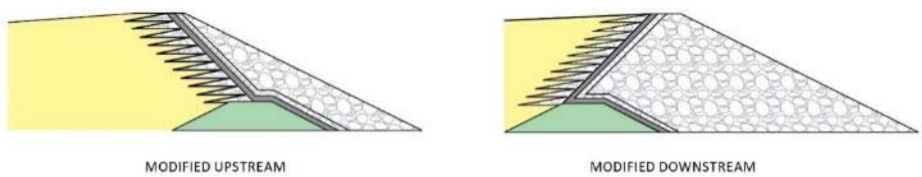


Fig. 4.3
Geometry of modified upstream and modified downstream centerline dams

4.5. DESIGN PRACTICES FOR UPSTREAM CONSTRUCTION

4.5.1. Background

Upstream construction involves raising of a tailings dam by placing tailings on the upstream side of the dam embankment, essentially placing over previously discharged tailings as shown on Figure 4.4. The outer zone, referred to as the structural zone (shown with a red dashed line), becomes the retaining structure. This type of construction offers significant economic advantages, however there are inherent uncertainties in the properties of the tailings and pore pressure conditions.

The method of constructing dams by the upstream method is discussed in ICOLD B106 (ICOLD 1996), in which several variations are described, including:

- Cycloning – where the tailings are separated into coarse and fine particles using cyclones, with the coarse sand used to form the structural zone;
- Beaching using spigots or spray-bars, with crest raising by compacted earth fill (Figure 4.4); or
- Paddock Construction using cellular construction of tailings placement near the tailings slope that desiccates and provides freeboard, sometimes referred to "daywall" construction.

ICOLD Bulletin B 121 discusses a key risk inherent in upstream construction being the potential for tailings in the structural zone to remain saturated at low density, resulting in tailings being in a contractive state, susceptible to static or dynamic liquefaction. The extent of saturation is sometimes difficult to determine with perched water tables being common due to segregation and layering. Piezometers cannot be relied on to give an accurate picture of the phreatic surface, particularly if vertical drainage is occurring and/or perched water tables are present.

Caution should be applied when considering upstream construction, particularly when using fine tailings that have poor drainage characteristics and in climates where drying effects might be limited and/or in areas of moderate seismicity.

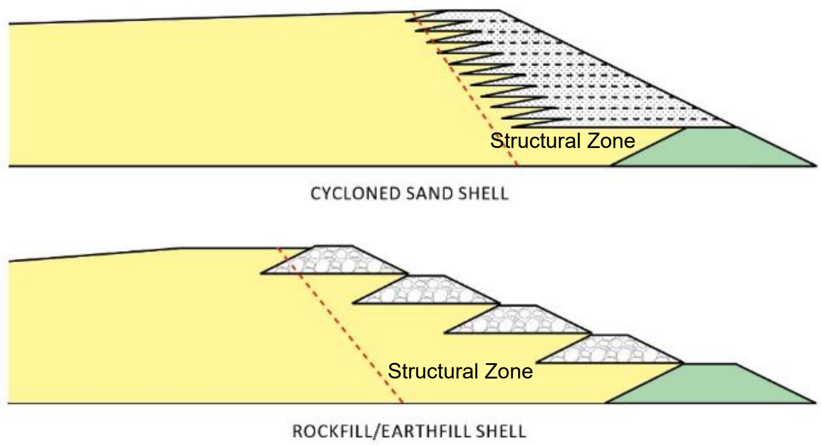


Fig. 4.4
Typical examples of upstream dam construction

4.5.2. Design Practices

Despite being less common in some regions, improved design methods and good construction control can result in upstream construction meeting design requirements. Upstream construction can be achieved in a variety of ways, but the fundamental requirements are no different to any other dam or earth structure, providing the factors of safety are achieved. The first step is to assess if the tailings in the structural zone could be prone to static or dynamic liquefaction and ensuring that there are adequate factors of safety against undrained strength conditions. Typical peak undrained shear strength ratios for tailings are on the order of $Su/\sigma_v' = 0.25$ to 0.35. Where sufficient drying time is provided, it may be feasible to achieve peak undrained shear strengths of up to $Su/\sigma_v'=0.5$. It is important to note, however, that as the dam height increases, the apparent over consolidation due to desiccation may be negated, resulting in reduced Su/σ_v' values.

Where static or cyclic liquefaction could occur, the residual undrained shear strength ratio can be of the order of $Su_r/\sigma_v' = 0.10$ or lower.

Mechanical compaction of tailings within the structural zone has been successfully carried out for upstream dams with dozers, as shown on Figure 4.5, and is an effective way of assuring density and resistance to static or cyclic liquefaction. Similarly, mud farming and cell construction, as described in Section 3.8.3 and evaporation cells Section 3.8.1, respectively, may be used to improve liquefaction resistance.

Fig. 4.5
Compaction of upstream tailings dam using dozers (photo courtesy of R. Donnato)

Upstream tailings dams have numerous operating and design considerations that influence their stability, including:

- Operation variability including, for example, changes in ore grind, mineralogy, and solids concentration, which influence tailings deposition and can result in lower strength zones.
- Inclusion of permafrost in cold climates which become part of the dam structure.
- Segregation of tailings on the beach, including operational periods where the slimes pond may encroach within the structural zone of the dam.
- Challenges with obtaining undisturbed samples for laboratory testing. Sample disturbance can cause consolidation of the sample, which may lead to overestimation of the strength and underestimation of the sensitivity of the sample. In situ cone penetration testing (CPT) often provides the most valuable data for assessing tailings parameters.
- Underdrains placed within the structural zone can become less effective with time due to tailings consolidation. Perched water levels can occur between layers of finer and coarser tailings.
- Seepage, consolidation and stability modeling are challenged by the inherent inhomogeneity of the tailings deposit.
- Consolidation of tailings occurs over a long period of time and affects the closure period where large settlements may occur. Settlement during operations may increase down-drag on decant towers. Differential settlements may also promote cracking of dam fills used for raising the dam.
- Amplification of seismic loads through the loose tailings are greatest at dams with low spectral periods.
- Determination of residual undrained shear strengths for post seismic stability analysis is challenged by limitation on laboratory testing and sample representativeness.
- Mud farming (Section 3.8.3) and evaporation cells (Section 3.8.1) may be used to increase the density of tailings within the structural zone.

4.6. DESIGN PRACTICES FOR HIGH DENSITY THICKENED AND PASTE TAILINGS

4.6.1. Background

Technologies for producing high-density thickened and paste tailings are described in Section 3.4 and Section 3.5 of this Bulletin. High-density thickened/paste tailings facilities involve delivery, in a pipeline, of a high-density thickened or paste tailings (typically ~60% to ~75% solids concentration and shear yield stresses from 40 Pa to 200 Pa) to the tailings facility. Due to the high shear yield stress of the tailings, positive displacement pumps may be required. The tailings are deposited hydraulically, in a loose state, and beached at somewhat steeper slopes than unthickened slurry.

Containment dams are still required but may be smaller than those with conventional tailings facilities if long beach slopes are practical. A schematic illustrating the principal difference between the central cone discharge versus conventional is shown on Figure 4.6. High-density thickened/paste tailings facilities are usually operated with no, or minimal, ponds on the tailings surface. Compared to conventional tailings facilities, less water is released from the deposited tailings as they consolidate. This water, along with precipitation and runoff, collects next to the dam and is directed off the surface to external collection ponds where it may be reclaimed to the ore processing facility, or discharged. Depending on the topography and available land, the containment dam can be small and, as it is not storing water, could be a simple earth fill structure.

One of the most important considerations with thickened/paste tailings production is that it is a sensitive process that requires constant and controlled operation of the system and continual adjustments to upsets due to ore variability. High density tailings typically aim to have ~70% solids concentration for hard rock tailings, although consistent solid concentrations achieved to date have been lower.

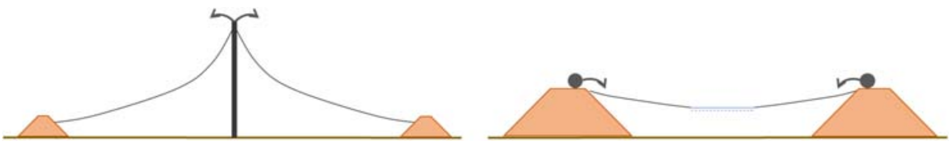


Fig. 4.6
Schematic showing principal difference between central discharge (left) and perimeter Discharge (right)

4.6.2. Design Practices

Thickened/paste tailings may be discharged from a central point (central cone discharge or central thickened discharge) on relatively flat ground, or from a side hill. The facilities are often located in arid areas with flat ground and minimal restraints on the facility footprint. Design considerations for the facilities include:

- Capital costs of the dams may be lower due to their low height and simple design section (they are not storing water). Capital costs of thickening and the tailings discharge system may be higher.

- Challenges with getting consistent slurry solid concentrations of > 60% with variability of thickening, ore types, mill feed, etc. Operational requirements for close control of flocculants, flows, density, pressures, and instrumentation.
- Challenges with obtaining consistent steeper beach slopes, particularly with long beach slopes (e.g., > 1 km) (See Figure 2.15). Periods of lower thickener density flatten the beach slopes. Cold climate influences which may flatten frozen beaches during thaw periods.
- Requirements for external ponds to manage the design flood events and requirements for safely transferring the surface runoff to the water storage ponds.
- Oxidation of PAG tailings and management of acidic runoff water.
- Footprint requirements for storage to limit the height of the perimeter containment dam.
- Water recovery is maximized in the process plant, which minimizes the requirements for water management at the tailings facility.
- Tailings are less susceptible to segregation and should have increased water retention capacity and lower hydraulic conductivity than segregated tailings.
- The closure configuration is closer to a stable landform, although closure cover costs for a larger footprint may be higher than a conventional facility. The high cost of capping soft slime ponds may be avoided.

4.7. DESIGN PRACTICES FOR FILTERED (DEWATERED) TAILINGS DISPOSAL

4.7.1. Background

Technologies for filtering are described in Section 3.6 of this Bulletin. Filtered tailings facilities involve delivery, by truck or conveyor, of tailings that are dewatered such that they are partially-saturated and act like a soil rather than a fluid. Filtered tailings typically need to be dewatered to 85% to 88% solids concentration, often near optimum moisture content, to facilitate compaction. Typically, the filtered tailings form the containment structure ("structural zones") and uncompacted tailings, which can have a lower solids content, can be placed in the interior. Facility seepage and runoff are collected and managed in external collection ponds. Figure 4.7 shows a schematic of a typical filtered tailings facility.

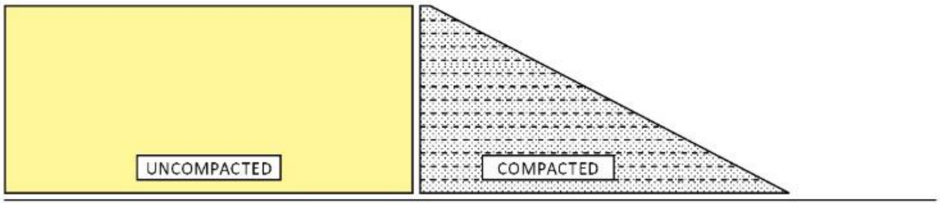


Fig. 4.7
Schematic of a filtered tailings facility

4.7.2. Design Practices

If the filtered tailings product is saturated and placed without compaction in a loose state, it may behave as a contractant soil. Consequently, the stability of the pile needs to consider undrained strength stability and the potential for static or dynamic liquefaction. If required for structural stability, the outer shell of the filtered tailings pile may require compaction and/or placement of drainage layers. Environmental controls for the piles may still require liners and water treatment, particularly if the tailings are PAG or in a sensitive environmental setting.

Design considerations for filtered tailings facilities include:

- Consistency of mechanical operations and constructability during the range of climatic conditions; provision for alternate storage and/or management during system upsets.
- Trafficability and requirements for off-site borrow materials for access roads onto the piles and soil covers.
- Consistency of moisture content to allow controlled compaction.
- Requirements for seepage control, e.g., liners in the base of the pile and leachate collection systems; management of construction pore pressures.
- Management of surface water during extreme precipitation and/or snow melt events and safe transport of contaminated surface water to the water management ponds.
- Opportunities for co-disposal with mine rock.
- Opportunities for progressive reclamation of exterior slopes or piles.
- Dust management with compaction or irrigation.
- Water management to ensure that the “dry-stack” either remains unsaturated or is designed to allow saturation.
- Significant reduction in the risk of a catastrophic failure by elimination of storage of water on the surface of the TSF and the incremental increase in risk associated with water management facilities. Water management is still a significant issue to ensure that the “dry stack” remains unsaturated and stable.

4.8. DESIGN PRACTICES FOR DRAINED TAILINGS AND SEEPAGE CONTROL

The design of a tailings dam typically has at least two major objectives, geotechnical stability and environmental stability. For geotechnical stability, it is preferred to promote drainage of the tailings, possibly with installation of a drainage system under the tailings. This can be particularly advantageous for the long-term closure condition where elimination of a water pond and drainage of the tailings significantly reduces the risk. However, environmental constraints on tailings facilities may dictate a very low tolerance for seepage and, in the case of potentially acid generating tailings, a requirement to keep the tailings saturated for perpetuity. The application of tailings / geomembrane liner systems have shown to have an extremely low leakage rate (Rowe et al, 2017). Designers and Regulators need to carefully consider the advantages and disadvantages of internal drainage as part of the design process.

4.8.1. Other Dam Type and Containment Considerations

There are a wide variety of tailings dams, which include variations of the containment types described in the previous sections and the different tailing technologies (Section 3). Tailings storage technologies continue to evolve to meet site specific conditions and to respond to improved understanding of existing technologies and new technology developments. The following sections illustrate additional tailings storage and dam type considerations.

Co-placement and Co-mingling

Co-placement, described in Section 3.7.1 of this Bulletin, uses mine waste rock to construct a more robust landform tailings dam, or to place PAG waste rock into a saturated tailings facility. In both cases, the dams are designed to meet geotechnical stability requirements.

Co-mingling, described in Section 3.7.2 of Bulletin, combines tailings and waste rock to form a free- standing landform. In these cases, the facility design considerations would be like those described in Section 4.7 on filtered tailings.

Central Decant System

Where upstream construction is considered in an area of relatively flat topography, the use of a centrally located decant system can be appropriate. This results in a “ring dyke” dam arrangement with a perimeter embankment and a central decant pond, accessed by a causeway. The central decant allows the development of a perimeter beach that proportioned to manage rate of rise of tailings and allow progressive cycling of discharge around the perimeter to promote desiccation. The decant pond can be controlled either by a gravity decant structure, or by pumps. Water management considerations are most important where upstream construction is used with a central decant system, as the dam is often not designed to retain water and flood water is usually stored within the impoundment. Structural design of the buried decant towers and outlets is important, as failures can lead to serious dam safety incidents. The dam safety risk may be heightened by the potential for lateral cracking due to differential settlement of the perimeter embankment. An example of a central decant pond is shown on Figure 4.8.

Fig. 4.8
Ring dyke configuration (three cell arrangement) at Kalgoorlie Consolidated Gold Mines (KCGM), Western Australia (Courtesy Newmont Australia) (Tailings.info [n.d.])

Evaporation Cells

The use of evaporation cells to consolidate the tailings can be considered a variation of the upstream disposal method (Section 4.5) and an example of dried cell is illustrated on Figure 4.9. This practice is best suited to arid or semi-arid climates.

Fig. 4.9
Evaporation cell showing desiccated tailings (photo courtesy of, J. Pimenta d"Avila)

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