CHAPTER 11: MINE WASTE DUMP

1.0 Introduction

The Overburden of waste and uneconomic mineralized rock is required to be removed to mine the useful mineral resource in a surface mining operation. In this process a dump is formed by casting the waste material and dumping it in nearby area. The dump so formed is known as mine waste dump. Waste dump may be classified as internal and external dump. External dump is created outside the pit whereas internal dump is created inside back of the mining area.

These waste rock dumps are heterogeneous in terms of grain size and structure. The fragmentation of rock in a dump is a product of number of mechanical processes, like drilling, blasting, ripping, etc. Consequently, dump rock may range in size from clay particles to boulders (e.g. less than 0.1 mm to greater than 1 m in diameter). Natural gravity sorting of rock poured from a haulage truck onto a waste dump face may result in a vertical size distribution, finer materials tend to remain near the top and coarse materials tend to roll down the face toward the toe of the dump.

As most of the waste rock disposal facilities at open pit mines are constructed with run off mine materials using trucks, there is very little control over the exact size distribution of these materials. However, modern blasting technology allows considerable control on the size of largest particles. In-pit crushing of waste rock is also done at a few mines to reduce the size of material, to transport it by belt conveyors out of the pit to the disposal facility. Often overburden and waste rocks are end-dumped from the trucks and the excess material is bulldozed over the storage facility edge to construct slopes at the angle of repose, where the outer slope is just stable under the static loading conditions at the site and is typically 37–40°.

The manner in which a waste rock dump is designed and constructed can also result in significant differences in structure. Commonly, construction of a dump progresses by addition of material to its top at the face, allowing waste rock to form a continuously renewed veneer on the face. The dump progresses outward horizontally, as successive layers are added to the face. However, some dumps are engineered in other ways, resulting in significantly different internal structures. For instance, in order to enhance stability and minimize the release of fine sediments into the down-stream environment, some dumps are designed with a French drain, a layer of
coarse and durable rock such as chert, placed at the base to allow unrestricted flow of stream through base of the dump. Waste rock dumps are also constructed in layers resulting in a sequence or stack of dumps.

The shape of a mine dump is mainly based on the nature and topography of the area, where they are emplaced. Mine dump can take the shape of one or a combination of many different configurations, such as valley-fill, cross-valley, side-hill, ridge, or heaped, depending on the topography of the area. The dumping method of material can be used to classify dumps into five basic types:

- **End dumping** - dumping rock over dump face resulting in some particle size segregation down slope towards the toe of the rock pile, with particle size generally increasing

- **Push dumping** - dumping from trucks, followed by leveling and pushing by tractors and shovels resulting in particle size segregation: finer at the top and coarser at the toe of the dump slope

- **Free dumping or plug dumping** - dumping in small piles on the surface of the rock pile, grading the material, and compacting in layers or lifts resulting in dense layers with no real particle size segregation

- **Dragline spoiling** - deposited on the surface without construction of lifts and minimal compaction resulting in dense layers with no real particle size segregation because of relatively low overall height of the spoil piles, typically used in coal mining

- **Mixing of waste rock with tailings.**
2.0 Method of Construction in lift section

Dumps are usually constructed in a series of lifts following either descending or ascending sequence. Ascending construction is advantageous, as toe of each lift is supported on the preceding lift in this case. Figure 1 & 2 show the construction of mine waste dump in lifts. The method of construction selected is based on a combination of factors such as minimizing haulage distance, accessibility, available capacity and dump stability. Stability can be enhanced by judicious use of wrap-arounds, terracing, restricting lift heights to limit shear stresses on the foundations and the length of potential runout, and dumping in the direction of valley contours rather than downslope.

Construction in lifts depends on the geotechnical properties of dump material, cost of haulage, ease of final grading, etc. Surface slope of top of the dump depends on run-off of water, drainage and safety. The control of run-off water and drain recharge is also very important in design of mine waste dump. As the dump is composed of blasted rock material, proper dust control and dust suppression methods should be used.

Figure 1 : Construction of mine waste dump in lifts
Figure 2: cross-section view of dump Lifts
Figure 3: Typical layout of Dump
General type of fills are valley fill, Sidehill, Cross-Valley fills, Heaped Fills, etc. Valley fills fill the valley partially or completely (figure 4). The surface of the dump is usually graded to prevent impoundment of water at head of the valley. Valley fills, which do not completely fill the valley, may require construction of culverts, flow-through rock drains or diversions depending on the size and characteristics of the upstream catchment. Sidehill fills are constructed on sloping terrain and do not block any major drainage course, as illustrated in Figure 4. Dump slopes are usually inclined in the same general direction as the foundation. Toes of Sidehill fills may be located on the slope or on flat terrain in the valley bottom. The Cross-Valley fill is a variation of the Valley fill. As illustrated in Figure 4, the embankment extends from one side of the valley across the drainage to the other side of the valley. The upstream portion of the valley is not completely filled and fill slopes are established in both the upstream and the downstream directions. Heaped fills are stacked or piled fills, consisting of mounds of waste with slopes formed on all sides. Foundation slopes are generally flat or gently inclined.
Ascending construction requires development of lifts starting at base of the structure and progressing to the ultimate height. Material is placed in a controlled manner in relatively small thickness. Once a lift is completed, the next lift is placed on top, and the sequence is continued until the ultimate dump height is reached. This controlled construction technique is commonly used in situations where sensitive foundation soils exist and incremental loading allows these soils to drain and consolidate through strain hardening at rates suitable for foundation stability. Rapid loading of such soils may result in strain softening and static liquefaction due to generation pore pressure trending to the overlying weight of material. This type of construction is generally more expensive since it involves more material handling than other construction methodologies and requires monitoring.

Descending construction is placement of material from the operating height which allows the dump to develop based on natural material strength. Material is placed from the ultimate height, or crest of the dump. Typically, material is end-dumped from the haul truck at this elevation. Variations in this procedure include the dump-short-and-push method, where trucks dump on the safety of the platform without approaching a potentially unstable crest and the material is then pushed by crawler dozer over the crest.

A common development for descending dump is the construction of wraparound dumps. These dumps include the use of secondary benches and are another means of descending construction, where rock is placed on the slope of an existing dump at a lower elevation than the dump platform. This method is only possible by achieving access to the specified elevation, and is often carried out as mining progresses to lower elevation. The benefit of wraparound berms is a general increase in stability for the overall dump. Placement of material in a wraparound berm is analogous to placing a toe berm, effectively flattening the overall slope, increasing shear resistance of the mass, and lessening the shear stresses induced in the foundation materials.
Types of slope failure in mine dump:

Figure 5 shows the common types of failure occurring in mine dumps.

<table>
<thead>
<tr>
<th>Surface slide</th>
<th>Edge slide</th>
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<td>Shallow flow slides</td>
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<td>Block Translation</td>
<td>foundation circular failure</td>
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<tr>
<td>Circular Arc failure</td>
<td>Toe spreading</td>
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Figure 5: different types of possible dump failure types
3.0 Methods of Stability Calculation

The method of stability calculation for a dump design is dependent on the anticipated mode of failure. The potential modes of failure for a specific site conditions are often difficult to assess. In most cases, the method of stability calculation is based on a generalized slip surface, which may be a plane, an arc, or a combination of both. These generalized analyses include identification of the slip surface with the lowest determined factor of safety while treating the dump mass as a homogenous body. The shear strength of dump depends on the following parameters (Hawley, 2001; Holtz and Kovacs, 2003):

- Particle shape and roughness of grain surface
- Grain quality: weak rock materials such as shale has lower friction angle compared to strong rock materials such as granite
- Grain size: friction angle increases or decreases with increase in grain size
- Grain size distribution: friction angle typically decreases with decreasing coefficient of uniformity of grain size
- Specific gravity
- State of compaction or packing: friction angle typically increases with increasing density or decreasing void ratio
- Applied stress level: friction angle decreases with increasing confining stress, resulting in a curved strength envelope passing through the origin instead of the classical straight line
- Definition of failure conditions: drained or undrained, and
- Degree of saturation
3.1 Shear Strength of dump material

An increase in the proportion of coarse material in fine-grained granular soil results in an increase in friction angle (Holtz and Gibbs, 1956; Holtz, 1960). Typical friction-angle values for medium-dense sand can range from 32º to 38º, while typical friction-angle values for medium-dense sandy gravel can range from 34º to 48º (Das, 1983). Rockfill particles, similar to those found in mine rock piles have internal friction angles in the range of 40º to 50º, the lower end of the range corresponding to fine-grained material, and the upper end of the range corresponds to coarse-grained material (Leps, 1970).

Lewis (1956) concluded that the increase in friction angle with increasing size of particle sizes, was attributed to increase in interlocking particles, interference of particle shear, and increase in dilatational tendencies for the larger particles. For a given void ratio, the smallest sized material has the highest angle of internal friction, and the angle of internal friction decreases as the maximum particle size increases (Leslie 1961).

The angle of shear resistance increases with the size of the particles. This is due to the high stress build up at the contact surface of the angular particles with increasing particle size causing high particle breakage. This also accounts for the decrease in internal friction angle or shearing resistance with particle size.
3.2 Particle shape, roundness and grain surface texture

The shape and the roughness of grain surfaces also the friction angle and the slope stability of dumps. Robinson and Friedman (2002) found that increased angularity of grains increased the friction angle. In fact grain texture is dependent upon material composition, grain formation, separation from the matrix, transportation, and depositional environments (Cho et al., 2006). Similar investigation made by Barton (2008) suggest that strength of dump material is similar to the strength of rockfill and rock joints, because these materials have similar strength envelopes due to the effects of point of contacts. There has been a profound effect of roughness and particle size on shear strength as well. As roughness increases so does the friction angle.

3.3 Effect of moisture condition on shear strength

The effect of moisture on shear strength of soils is very important in considering slope stability. Kjaernsli and Sande (1963) showed that the shear strength of dry soil samples is higher than that of saturated and submerged samples. However, it also depends on the type of soil or material and its partial side distribution.

Horn and Deere (1962) observed that increases of surface moisture causes the coefficient of friction to increase for massive-structured minerals such as quartz as compared to a decrease for minerals having layer-lattice structures such as mica. He found that sliding friction on different minerals under similar testing conditions show different coefficients of friction, but minerals of the same type from different origins had the same frictional characteristics.

4.0 Factors Affecting Dump Stability

A variety of factors act in combination to control the stability of a mine dump. The main factors are discussed below.

4.1 Dump Configuration
The configuration and the size of a mine dump have a direct impact on its stability and potential size of failures. The primary geometric variables are:

- **Height of the dump:** It is defined as the vertical distance from the dump crest to the ground surface at the dump toe. Dump height typically ranges from 20m to more than 400m. It is an important characteristic for stability, mode and speed of failure, and potential runout distance. In general, dump height is predetermined by the mine site physiography and mining rate. The ultimate toe of a dump is dictated by the volume of material to be placed depending on the size of the area or the depth of the valley.

- **Volume:** Small dumps are considered to contain less than about 1 million m$^3$, while large dumps have more than 50 million m$^3$. Medium sized dumps have volumes in the range of 1 to 50 million m$^3$.

- **Slope Angle:** The overall dump angle is measured from crest of the uppermost platform to the toe. The normal range of dump slopes is between 26° to 37°, the lower value commonly adopted for reclamation whereas the upper value corresponds to the free dumped cohesionless rockfill. Slopes steeper than 37° may also occur if the dump material contains appreciable fines or cohesive material, or consists of very large, angular boulders.

- **Foundation Slope and Degree of Confinement**

  The foundation slope and degree of confinement afforded by shape of the foundation also affects dump stability. The most favourable situations are a decreasing slope towards the toe (i.e. a concave slope), and three-dimensional confinement within a valley.

4.2 **Foundation Conditions**

Poor foundation conditions are cited as the most frequent cause of dump slope instability. The foundation of a dump may have a variety of rock formation from saturated soil to competent bedrock. The presence of water within the voids of a dump seriously affects the dumps stability
depending on the quantity or elevation of the phreatic surface (limit of saturation). Inflows of water to a dump include precipitation, snow melt, surface runoff, and foundation seepage.

Presence of weak saturated soil or similar zones in the foundation affects stability of a dump by allowing deformation of the toe material. Similar conditions may arise where material is placed on previous failure debris. Debris often exhibits a much lower strength than in its original state due to changes in particle size and shape, and moisture content.

Surface runoff is controlled to a large degree by the physiography of the site, however manmade diversion systems can be constructed to minimize this amount. Foundation seepage can occur in the form of groundwater springs which are often controlled by the geologic structure.

The potential presence of groundwater springs needs to be investigated prior to dumping. It is not uncommon for these features to be located in gullies or creek beds where contact with the natural groundwater table can be expected. Dump configurations such as valley fills or cross valley fills require an assessment of the drainage characteristics of the foundation and fill material, to prevent built up of water within the dump.

Competent foundations are formed of highly competent bedrock or soil of equal or greater strength than the dump materials, and which is insensitive to pore pressure generation or strength reduction due to loading. Intermediate foundation is formed of intermediate material which consolidate and gain strength with time, but may be subjected to pore pressure generation and strength loss if loaded and sheared too rapidly. Weak foundations are formed of weak materials which cannot safely be loaded beyond a limiting level of shear stress, and which does not gain strength at a significant rate by consolidation. This is frequently the case where clay layers occur within the foundation soils. Such foundations are also subjected to potential liquefaction or high pore pressures.

4.3 Dump Material Properties

Properties of dump materials include gradation, shear strength and durability, etc. The most favourable dump materials are composed of hard and durable coarse rock with little or no fines and are commonly associated with metal mines. The least favourable materials are formed of soft and degradable rocks with significant fines, such as mudstones or shales, which are commonly associated with coal measures or heavily weathered or altered rock masses. However, of primary importance is the percentage of fine particles which may absorb water (especially clay minerals), settle and blind natural drainage paths within the base of dump, and
may impart some degree of apparent cohesion causing oversteepening in localized areas. In general, the higher the percentage of fines, the poorer is the overall stability of the dump.

The shear strength of dump material depends on rock types and its compositions, the unconfined compressive strength, weathering and slaking potential, and the respective particle sizes. The strength of the resulting combination of material is generally based on a comparison of similar rock types and their relative compressive strengths and gradation.

Materials with low durability weather rapidly to finer particles in the natural dump environment due to exposure to atmospheric moisture, wetting and drying, freezing and thawing, and high particle to particle loads. Movement within the dump also degrades the material and results in a rounded rather than angular shaped rock, with a coincident reduction in friction angle for the material.

The mine geology may change dramatically from bench to bench. Under such condition, strong and competent rocks may be placed under weak and altered rocks on the platform and down the face. In this scenario, further loading even of competent material, may result in instability due to the presence of weak planes.

Most mining operations encounter a range of material types in their rock and soil materials. Soil should be excluded from mine dumps, as it hinders drainage and introduces zones of lower shear strength. Such soil should be placed in specifically designated and designed dumps or stockpile sites.

### 4.5 Dumping method

Mass dumping leads to rotation failures where the fine grained material behaves as a weak homogeneous mass. In the end-dumped dump state, it is very sensitive to pore pressure increases caused by rapid loading, precipitation, and foundation seepage pressures.

Face dumping causes formation of a plane of weakness along the face. Under such condition, continued use of the dump, even for dumping of good quality material is susceptible to failure along this plane.

Crest Dumping or rapid dumping of fine grained material on the crest may result in local oversteepening. This is due to the apparent cohesion imparted by an increase in moisture content. Oversteepening has been documented to have caused crest slopes in excess of 43°.

The problem of poor quality material is exacerbated by addition of water in the form of runoff or direct precipitation. It is important therefore to minimize the impact of precipitation on dump
using various measures such as diversion of surface runoff, and adequate foundation preparation to minimize seepage inflows.

**Handling and Placement:** Mechanical handling of dump material causes some breaking of poor quality rocks. The more handling-intensive is the placement method, the more is the breakage expected. Of the commonly used placement methods, end dumping usually causes the minimum degradation. Dumping short and dozing adds an extra degree of breakage. Designs requiring placement in lifts and those requiring compaction suffer the effects of further degree of breakage. Heavy equipment (e.g. dozers and haul trucks), which by necessity travels on dump surfaces, also have a deleterious mechanical effect on the materials.

### 4.5 Dumping Rate

The impact of loading rate on physical stability of dump is very important. The placement of loose blasted rock or soils in a manner which does not allow for sufficient time for the material to develop strength at reasonable density will experience significant settlement. Rapid loading and increase in toe loading associated with slope and crest deformations overload the toe block.

High rate of dumping may result in generation of excess pore pressures. In such cases, dumping rate may have to be controlled and pore pressure monitored during construction to ensure that excess pore pressures are effectively dissipated and foundation stability is maintained.

### 4.6 Seismicity and Dynamic Stability

The most significant impact on stability due to earthquakes appears to be potential liquefaction of susceptible foundation materials. However, saturated fine grained dump materials may also be subjected to liquefaction. Dynamic ground motions induced by nearby blasting associated with mining could affect dump stability.

### 4.7 Topography

Topography has a direct influence on dump stability in different ways. Mine dump instability on steep terrain may be due to the difficulty in achieving adequate dump density and therefore the maximum shear strength of the material. Other problems include slope regions with increasing slope angles in the vicinity of the toe or side flanks. Flat or near horizontal slope is more stable
whereas, steep slopes approaching the natural angle of repose for the overburden dump material are likely to exhibit ravelling, or other planar instability.

### 4.8 Dump drainage condition

Piezometric conditions of a dump and its associated foundation are of primary importance for the assessment of dump stability. In most cases, large coarse dump materials have sufficient permeability so as to render the dump an effectively drained structure. The material placed using the end-dumping technique segregates and coarse material arrive at the toe/foundation contact thus enhancing the permeability. End-dumping from large heights and simultaneous construction of a flow-through drain to enhance permeability are apparently co-benefits of the most cost efficient dumping methods.

Percolation of rainwater through the dump carries existing fine particles towards the dump foundation level. The generation of fine particles over time within the dump by natural slaking, weathering, and high point to point loads adds to the fine particle load. Ultimately these fines settles and cause blinding of the foundation interface contact within the dump, severely reducing the capacity of the drained structure. The presence of perched water levels may also be created as fine grained, poor quality material is placed in one area or elevation of the dump. This may lead to localized areas of deformation and instability. The most common solution has been to construct diversion ditches around the dump. Occasionally, culverts or decant systems have been built to carry water under a dump. If surface water flows on dumps are unavoidable, contouring and ditching should be provided to channel the water. Ditches should be lined with coarse rock armouring to control erosion, designed according to hydrological requirements. Low permeability linings to control seepage may also be required (figure 6).
Figure 6: Drainage layout and Interception
5.0 Material testing and properties

The engineering properties of foundation and dump materials are required for design of dump slopes. Selecting and obtaining representative samples for materials testing, interpreting results and applying them to design requires a thorough understanding of the various components of the physical environment. The type and amount of testing required varies, depending on the complexity of site conditions, the location, type, size and configuration of dump, the environmental sensitivity of the site, etc. For large dumps, or dumps located on a complex and environmentally sensitive site, substantial detailed testing may be required. In cases where a probabilistic approach to design is adopted, a large testing program may be required to supply sufficient data for statistical analysis.

5.1 Bulk Gradation

The overall gradation of a mine rock has direct impact on the shear strength and the permeability characteristics of dump slopes. In general, coarser materials with few fines, have higher strength and hydraulic conductivity than materials with appreciable fines. Where mine rock contains less than about 10% fines, the most important factors controlling gradation are hardness and compressive strength of the rock fragments. Coarse dump materials generally derive their strength from interparticle contacts and exhibit engineering properties similar to rockfill.

The gradation of mine rock depends on a wide variety of factors, including: lithology, durability, frequency and character of discontinuities, blasting and excavation technique, handling and transportation, placement methods, and other factors. Gradation may also change with time, due to mechanical or chemical breakdown (e.g. freeze thaw, swelling of clay minerals, oxidation, etc.).
5.2 Plasticity of Fines

Plasticity of the fines may have an impact on the shear strength characteristics of the material, and may be indicative of the type of clay minerals contained within it. If a substantial component of silt sized or finer material occurs within the mine rock, the plastic limit of this material should be determined in the laboratory. Atterberg Limit test may also be conducted on mechanically disaggregated, fine-grained sedimentary rocks.

5.3 Index Properties and Classification

Index properties provide an indication of some of the key engineering properties, such as shear strength, permeability and consolidation. Parameters such as natural moisture content, unit weight and specific gravity, provide information on the volume-weight relationships of the soil, which are used in a wide variety of calculations including consolidation rates, pre-consolidation pressures, porosity and stability calculations, etc.

5.4 Hydraulic Conductivity

A knowledge of hydraulic conductivity of various soil units is necessary for seepage analysis, and prediction of piezometric conditions within the foundation. In situ field measurement is usually the most reliable method for obtaining hydraulic conductivity data.

5.6 Consolidation

Where dumps are founded on fine grained soils, an assessment of the consolidation characteristics of the underlying soils is required. This information is necessary to predict foundation settlements and the potential for generation and dissipation of excess pore pressure due to dump loading.
Consolidation settlement of foundation soils may also reduce infiltration and improve the shear strength characteristics of foundation materials. Consolidation of foundation soils induces strain in the dump material with a consequent change in shear strength and behaviour.

5.7 Strength

The shear and compressive strength characteristics of the foundation materials are required for assessment of foundation stability and its bearing capacity. Where foundation conditions are complex, or foundation soils are fine grained, soft or susceptible to consolidation, pore pressure generation or other adverse effects, more detailed field and laboratory testing would be required. The number and type of tests to be conducted, and conditions of testing, depend on the complexity of site conditions, the nature of the soil to be tested and the loading conditions to which it will be subjected.

The effective shear strength of dump materials depends on a wide variety of inter-related parameters including intact particle strength and strength anisotropy, particle angularity, gradation, basic surface roughness and frictional properties, lithologic composition, mineralogy, degree of saturation, and others. Shear strength may also change with time due to consolidation, degradation due to freeze-thaw, swelling or slaking, oxidation, leaching or other chemical changes or strains induced by foundation or internal adjustments.

The common practice in assessing the shear strength of dump materials for analysis and design is to assume a linear Mohr-Coulomb type failure criteria, with no cohesion and a friction angle represented by the natural repose angle of the materials. Repose angle of mine dumps typically range from 35° to 40°. This relatively simplistic approach for evaluating shear strength is considered reasonable for relatively small to moderate size dumps where internal stresses are low in comparison to the intact rock strength and dump materials contain only limited amounts of fines (i.e. <10% passing No. 200 mesh), and dump materials are not subject to degradation.
5.8 Mineralogy and Soil Chemistry

Mineralogy and chemical composition of overburden material may be important. The presence of certain clay minerals may fix some contaminants or slow their release. Overburden soils may also tend to buffer surface and groundwater. The presence of swelling or low strength clay minerals can have a significant impact on the shear strength characteristics and behaviour of the dump material. It can also influence the durability and strength of foundation bedrock.

5.9 In Situ Density

The in situ density of soil directly affects its shear strength which in turn responsible for affecting the potential of foundation settlement and the resistance to liquefaction during construction or in an earthquake.

5.10 Compaction

Assessment of the compaction characteristic of the foundation soils is required if foundation remedial or mitigative measures are contemplated, such as proof rolling or berm or liner construction. Field measurements are generally restricted to density measurements on test fills or proof rolled soils using nuclear densometers, sand cones or volumeters. Laboratory compaction testing usually consists of Standard or Modified Proctor density testing.
12.6 Introduction

Almost all waste materials produced at a mining and milling operation can be divided into two classes. Mine waste is that product which is mined but which is not processed before being placed on a waste dump. Tailing is that product which is discarded after mining and processing to remove the economic products. Processing may range from simple mechanical sorting to crushing and grinding followed by physical or chemical processing. It contains all other constituents of the ore except majority of the extracted metal. It may also contain heavy metals and other substances at concentration levels that can be toxic to biota in the environment. The mechanical stability of the tailings mass is poor because of its small grain size and high water content. The ultimate purpose of a tailing impoundment is to contain fine-grained tailings. The long-term cost of tailings disposal depend in part on mechanical stability and environmental integrity.

Tailings were disposed off where convenient and most cost-effective, often in flowing water or directly into drainages. Definition of impending stability concerns are raised in part by the use of tailings material in tailings dams or embankments. to mitigate these concerns, such embankments often rely on a certain amount of controlled seepage to enhance stability, which in turn affects environmental performance. Products are removed from their original location, broken up and placed in piles in which the conditions of oxidation, seepage, leaching and erosion differ considerably from those at their original location. This increases the potential considerably for wind or water erosion of surface materials and their transport into the environment. The potential for oxidation and leaching is also increased with the result that dissolved contaminants may be carried away from the pile into the environment.

Design of tailing impoundments depends on the quantity and the individual characteristics of the tailings produced by mining and milling operation as well as the climatic, topographic, geologic, hydro-geologic and geotechnical characteristics of the disposal site, apart from regulatory requirements related to dam safety and to environmental performance.
12.7 Failure Modes in tailing dams
The major slope failure in tailing dams result from rotational sliding, overtopping, foundation failure, erosion, piping, and liquefaction.

Rotational Sliding
Failure surface appears as a segment of horizontal cylinder, ranging from local sloughing of tailings at random areas along the face of an embankment to massive circular arc slides extending over the entire structure. Specifically, causes of rotational failure may include changes in the water table, changes in the permeability of foundation materials and disturbances to the embankment caused by vibration or impact loading, settlement of the foundation materials, etc (CANMET 1977).

Foundation Failure
Foundation failures are not uncommon among earth fill structures. Where a weak layer of soil or rock exists at shallow depth in the foundation below the structure, movement along a failure plane will occur if the earth fill loading produces stresses in excess of the shear strength of the soil in the weak layer (CANMET 1977).

Overtopping and Liquifaction
One of the most common causes of failure is overtopping by flood waters. Overtopping typically results when the volume of run-on entering an impoundment from improper diversion of surface water flows or excessive storm water flow exceeds the capacity of the impoundment. Because tailings embankments are constructed of highly erodible materials, the friction caused by rapid flow over an unprotected embankment crest may quickly erode a gully in the fill material, allowing sustained release to occur. Additionally, a rapid increase in pore pressure associated with large storm water inflow may result in the liquefaction of unconsolidated impounded sands and slimes. Sustained high flow over the crest of an embankment can thus result in a major failure of the overall impoundment within minutes.

Erosion
In areas of heavy rainfall, some form of protection against erosion is usually required. Tailings embankments may be susceptible to erosion failure in two major areas, embankment abutments and the embankment face. Erosion of embankment faces may result from rupture in tailings lines.
installed on the embankment crest. Typically, this type of failure is preventable with proper storm water diversion methods.

**Piping**

Piping refers to subsurface erosion along a seepage pathway within or beneath an embankment which results in the formation of a low-pressure conduit allowing concentrated flow. The resulting void space promotes progressive erosion extending upstream toward the source of the seepage. Excessive piping may result in local or general failure of the embankment or the embankment foundation itself.

**12.8 Tailings Impoundment Design**

Mine tailings produced by the mill are usually in slurry form. Disposal of slurry tailings in impoundments made of local materials is the most common and economical method of disposal. There are four main types of slurry impoundment layouts; valley impoundments, ring dikes, in-pit impoundments, and specially-dug pits. Slurry tailings are sometimes disposed in underground mines as backfill to provide ground or wall support.

Open-pit backfilling is also practiced where tailings are deposited into abandoned pits or portions of active pits. In active pits, embankments may be necessary to keep the tailings away from the active area. However, since seepage from the tailings can adversely affect the stability of the pit walls or embankments, it is unusual to see disposal in active pits.

In general, tailings impoundments are designed using information on tailings characteristics, available construction materials, site specific factors (such as topography, geology, hydrology and seismicity) and costs, with dynamic interplay between these factors influencing the location and actual design of the impoundment.

Tailings composition, pulp density, grading, and other characteristics are used in the design of tailings impoundments in three basic ways: tailings analysis to assess the potential use of tailings sands in constructing the embankment, analysis of tailings to be placed in the impoundment to determine their potential impact on structural stability and seepage characteristics, and mineralogical analysis to determine the potential chemical aspects of seepage or other discharges from the impoundment. Tailings are considered to be soils, subject to traditional soil mechanics.
patterns of behaviour.

**Mill Location**
Tailings are generally transported from the mill in slurry form, typically with a solid content from 15 to 55 percent by weight. This requires an extensive piping system for the tailings, as well as for pumping reclaim water back to the mill. Sites are located downhill from the mill to allow gravity flow of the tailings to the impoundment and to minimize slurry pumping costs. However, pipelines with steep gradients are avoided where possible.

**Topography**
In addition to distance and elevation, natural topography is one of the main considerations for the given impoundment volume required. The aim is to achieve maximum storage capacity with the least amount of embankment fill.

**Hydrology**
Surface water hydrology factors generally favour water diversion around the impoundment and minimization of water inflows into the impoundment.

**Geology and Ground Water**
Once the site screening criteria of mill location, topography, and hydrology are selected, geological considerations assume a critical role. In particular, site geology affects the foundation of the embankment, seepage rate, and the availability of borrow materials for embankment construction. Soft foundations, for example, may limit the allowable rate of embankment build-up in order to allow for adequate pore pressure dissipation. Sloping foundations and the presence of weak layers in the foundation may contribute to slope failure of the embankment.

**Foundations**
The foundation area beneath the embankment is assessed using the geotechnical properties. Weak material beneath the slope, such as buried slopes once exposed to weathering, snow covered surfaces over which additional material has been deposited, layers of fine material included in a coarse material embankment, and foundation strata of low shear strength, can cause rotational sliding. If a deposit of clay is extensively fissured, water penetrating into the fissures can seriously weaken the deposit due to dependency of the shear strength on softened material strength adjacent to the fissures. Compression or consolidation of the foundation can also cause appreciable settling of the overlying material, sometimes causing cracks in tailing embankments.
that can lead to seepage or piping. Permeability of the foundation significantly affects stability of an embankment. When an embankment is constructed on a foundation of saturated impervious clay, for example, the loading of the embankment creates excess pore water pressure in the foundation material. Because the immediate loading is taken by the water phase in the foundation material, there is no increase in shear strength and the rapid increase in loading can initiate embankment failures extending through the foundation. If the foundation material beneath the tailing dam is pervious, excessive seepage can lead to piping failure. All of these foundation factors are taken into account during design.

**Seismicity**

A method commonly used to determine the effects of the design earthquake on a particular site is to assume that the earthquake occurs on the closest known active fault. The fault is selected on the basis of geological studies previously conducted in the area. Attenuation tables are then used to estimate the magnitude of earthquake forces reaching the site as a result of the design earthquake occurring on the selected fault.

### 12.8 Tailings impoundments

There are two basic types of structures used to retain tailings in impoundments, the raised embankment and the retention dam. The four main types of impoundments include the Ring-Dike, In-Pit, Specially Dug Pit, and variations of the Valley design. The design choice is primarily dependent upon natural topography, site conditions, and economic factors. Most tailings dams in operation today are a form of the Valley design. Because cost is often directly related to the amount of fill material used in the dam or embankment (i.e., its size), major savings can be realized by minimizing the size of the dam and by maximizing the use of local materials, particularly the tailings themselves. Retention dams are constructed at full height at the beginning of the disposal whereas raised embankments are constructed in phases as the need for additional disposal capacity arises. Raised embankments begin with a starter dike with more height added to the embankment as the volume of tailings increases in the impoundment.

Tailings dams are built to allow the remains from processing ores to settle out from the water that is used in the processing. The construction of tailings dams can vary significantly and is
mainly dependent on the type of tailings being stored and the topography of the storage facility. There are four main types of tailings storage: water retention Dam, up stream dam, down stream dam and centre line dam. Table show the comparison between different types of water retention impoundments.

Comparison of Surface impoundment Embankment Types

<table>
<thead>
<tr>
<th>Mill Tailings Requirements</th>
<th>Water Retention</th>
<th>Upstream</th>
<th>Downstream</th>
<th>Centerline</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Suitable for any type of tailings</td>
<td>At least 40-60% sand in whole tailings. Low pulp density desirable to promote grain-size segregation</td>
<td>Suitable for any type of tailings</td>
<td>Sands or low-plasticity slimes</td>
</tr>
<tr>
<td>Discharge Requirements</td>
<td>Any discharge procedure suitable</td>
<td>Peripheral discharge and well-controlled beach necessary</td>
<td>Varies according to design details</td>
<td>Peripheral discharge of at least nominal beach necessary</td>
</tr>
<tr>
<td>Water Storage Suitability</td>
<td>Good</td>
<td>Not suitable for significant water storage</td>
<td>Good</td>
<td>Not recommended for permanent storage. Temporary flood storage acceptable with proper design</td>
</tr>
<tr>
<td>Seismic Resistance</td>
<td>Good</td>
<td>Poor in high seismic areas</td>
<td>Good</td>
<td>Acceptable</td>
</tr>
<tr>
<td>Raising Rate Restrictions</td>
<td>Entire embankment constructed initially</td>
<td>Less than 4.5-9 m/yr most desirable. Greater than 15 m/yr can be hazardous</td>
<td>None</td>
<td>Height restrictions for individual raises many apply</td>
</tr>
<tr>
<td>Embankment Fill</td>
<td>Natural soil</td>
<td>Natural soil, sand</td>
<td>Sand tailings or mine waste</td>
<td>Sand tailings or mine waste if production rates</td>
</tr>
</tbody>
</table>
### Requirements

<table>
<thead>
<tr>
<th>Requirements</th>
<th>borrow</th>
<th>tailings, or mine waste</th>
<th>if production rates are sufficient, or natural soil</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative Embankment Cost</td>
<td>High</td>
<td>Low</td>
<td>High</td>
</tr>
</tbody>
</table>

### 12.9 Tailings storage facilities

The main function of a tailing storage facility is the safe, long-term storage of process waste with minimal environmental or social impact. The design of each facility is specific to the mining operation and site conditions. The design life of tailings storage facility is effectively perpetuity, which means it should be able to survive in a stable form without human intervention. Tailings storage facilities are constructed over a long period and this must be reflected in the geotechnical stability evaluations.

Tailing storage facilities may be constructed using tailings sand or borrow materials for the embankment. The amount of coarse tailings material or suitable rock, as well as the regional seismicity, will govern the type of embankment constructed. The construction of the embankment is done in a series of lifts, during the operational life of the mine. Synthetic liners or compacted clay may be used to minimize seepage. The tailings are slurried via pipeline to the facility and deposited via a single point discharge, spigots or a cyclone, when the sand fraction is used to construct the embankment. In single point discharge and spigot systems, the tailings are usually deposited to form a beach against the embankment with the liquid collecting away from it. This reduces the seepage and increases the stability. The level of the tailings pond is controlled by decanting any surplus liquid, also referred to as supernatant. This can be done through an embankment drain, decant towers or a floating pump. The liquid is then returned to the processing plant or discharged.
12.10 Methods of Tailings Disposal

The use of tailings material is generally the most economical construction method. As discussed previously, some of the disadvantages of using tailings as dam-building material include high susceptibility to internal piping, highly erodible surfaces, and high susceptibility of the fine tailings to frost action. Also, loose and saturated tailings are subjected to liquefaction under earthquake shocks. Sand fractions, after being separated from the slimes, may be easy to compact using vibratory compactors to obtain a dense mass of strong material that has greatly increased resistance to liquefaction. The three methods of construction using tailings are upstream, downstream and centerline.

Raised embankments can be constructed using upstream, downstream, or centerline methods (figure 7). Each of the structures, for instance, is constructed in four successive lifts with constructing material and the fill capacity increases incrementally with each successive lift. They have a lower initial capital cost than retention dams, because fill material and placement costs are phased over the whole life of the impoundment. The choice available for construction material are increased because of the smaller quantity needed at any one time. Retention dams generally use natural soil, whereas raised embankments can use natural soil, tailings, and waste rock in any combination.
Figure 7. Embankment Types: (a) Upstream, (b) Centerline, (c) Downstream or Water Retention

Figure 8: Water-Retention type Dam for Tailings Disposal
12.11 Upstream Method

Upstream construction is the oldest and most economical method, and begins with a starter dam constructed at the downstream toe (Figure 9). It should be capable of passing seepage water and the downstream portion should be resistant to piping. The tailings are discharged peripherally from the crest of the starter dam using spigots or cyclones. This deposition develops a dike and wide beach area composed of coarse material. The beach becomes the foundation for the next dike. In some applications, dikes are mechanically placed and the discharge is used to build the beach only. These dikes can be built with borrow fill or beach sand tailings can be excavated from the beach and placed by either dragline or bulldozer. Either way, some type of mechanical compaction of the dike is typically conducted before the next stage of dam is constructed.

The single most important criteria for application of the upstream construction method is that the tailings beach must form a competent foundation for support of the next dike. Vick (1990) states that, as a general rule, the discharge should not contain less than 40-60% sand. This can preclude the use of upstream method for those mill tailings that contain very low percentages of sand. In addition to tailings gradation, several other factors can limit the applicability of this method. These factors include prelatic surface control, water storage capacity, seismic liquefaction susceptibility and the rate of dam raising. Upstream embankment construction offers few structural measures for control of the prelatic surface within the embankment. Vick (1990) identified four important factors influencing the phreatic surface location: permeability of the foundation relative to the tailings, the degree of grain sizes segregation and lateral permeability variation within the deposit, and the location of pounded water relative to the embankment crest. Tailings embankments constructed using the upstream method generally has a low relative density with high water saturation. This combination can result in liquefaction of the tailings embankment in the event of seismic activity. In addition, vibration of sufficient intensity and magnitude caused by blasting, trains, heavy trucks, etc., may cause liquefaction. The shear strength can be reduced to near zero such that the fluidized slimes easily burst through the remaining thin, unsaturated sand-dike shell and the dam collapses and flows.

Upstream construction is not appropriate in areas with a high potential for seismic activity. The rate of embankment raises is limited by the built-up of excess pore pressure within the deposit. This built-up of pore pressures can lead to a shear failure, which may result in breaching of the
dam and the release of contained tailings (Brawner 1973). The height, at which potential failures are triggered, depends on the strength of the tailings within the zone of shearing, the downstream slope of the dam, and the location of the phreatic line. Horizontal drainage zones may be installed during starter dike construction to help maintaining low pore pressure within the embankment.

The upstream method is used with most tailings dams worldwide. Because of its low cost, but it must be built and operated with great care and attention as it has the highest risk of failure among all the methods.

Figure 9: Upstream construction of retaining dam
Upstream dams are highly susceptible to **liquefaction** under severe seismic groundmovement. This may result from earthquakes, from mine blasting, or even from the movement of heavy equipment.

### 12.12 Downstream Method

The design requirements for downstream method of construction are similar to conventional water storage dams. It begins with a starter dam constructed of compacted borrow materials. However, this starter dam may also be constructed of pervious sands and gravels or with predominately silts and clays to minimize seepage through the dam. If low permeability materials are used in the starter dike, internal drains will need to be incorporated in the design. A variety of tailings depositional techniques can be used in conjunction with the downstream construction method, but peripheral spiggotting of tailings is very common. Coarse tailings can be spread in thin layers utilizing on-dam cycloning, or they can be hauled from a central cycloned stockpile, then spread and compacted. If the volume of coarse tailings is not sufficient to construct the dam, local borrow materials may be incorporated for part of the structure. If coarse rock is used, due to its porosity, a filter or impervious upstream membrane is required to prevent piping of the tailings through the rock.

The downstream construction method allows for incorporation of drains and impervious cores to control the phreatic surface. Drainage controls help to control the phreatic surface and minimize the chance for built-up of pore water pressures which reduce shear strength. Due to the ability to incorporate drains into the design, this method of construction is well-suited to conditions where large volumes of water may be stored along with the tailings solids. This method of construction provides a degree of stability not found in upstream construction due to the ability and ease of compaction, the incorporation of phreatic surface control measures and the fact that the dam raises are not structurally dependent upon the tailings deposits for foundation strength (figure 10).
A major disadvantage of this method is the large volume of fill material required to raise the dam. The increased volume of fill required can dramatically increase the cost of this method of construction if the tailings from the mill cannot provide a sufficient volume of sand.

12.13 Centerline Method

Centerline construction is similar to both the upstream and downstream construction methods in that the embankment begins with a starter dam and tailings are spigotted off the crest of the dam to form a beach. The centerline of the embankment is maintained as fill and progressive raises are placed on both the beach and the downstream face (Figure 12). The tailings placed on the downstream slope should become compact to prevent shear failure. The centerline method of construction provides some of the advantages over the other two methods while mitigating some of the disadvantages. As in the downstream method, drainage zones can be incorporated into the
construction. A wide beach is not mandatory and this method is amenable for use with tailings that contain a relatively low percentage of sand. Since less sand is required, the dam raises may be added faster than that in the upstream or downstream methods. Coarse gradation of the tailings is necessary if rapid drainage is required to provide support for construction equipment. Although this embankment type is not amenable to permanent storage of large volumes of water, short term storage of water due to heavy precipitation events or mill shutdown does not adversely affect the dam stability.

Figure 12: Example of tailing embankment

If the embankment has been properly compacted and good internal drainage is provided, this embankment is resistant to seismic activity as well. Even if the slimes placed against the upstream slope liquefy, central and downstream portions of the dam may remain stable due to their good compaction and drainage characteristics.
Downstream Construction Method

Upstream Construction Method

Centerline Raise Construction Method