TAILSAFE

Sustainable Improvement in Safety of Tailings Facilities
TAILSAFE

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Report

Tailings Management Facilities
- Intervention Actions for Risk Reduction -

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Tailings Management Facilities – Intervention Actions for Risk Reduction

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Other reports of the TAILSAFE project:

Witt, K.J. & Schönhardt, M. (Eds., 2004): Tailings Management Facilities – Risks and Reliability. Report of the European RTD project TAILSAFE, http://www.tailsafe.com/, 176 p.

Engels, J. (Ed., 2004): Tailings Management Facilities – Intervention Actions for Risk Reduction. Report of the European RTD project TAILSAFE, http://www.tailsafe.com/, 150 p.

Witt, K.J. & Wudtke, R.-B. (Eds., 2004): Tailings Management Facilities – Implementation and Improvement of Design and Authorisation Procedures for Proposed Tailings Facilities. Report of the European RTD project TAILSAFE, http://www.tailsafe.com/, 24 p.

Xenidis, A. (Ed., 2004): Tailings Management Facilities – Implementation and Improvement of Closure and Restoration Plans for Disused Tailings Facilities. Report of the European RTD project TAILSAFE, http://www.tailsafe.com/, 54 p.

Engels, J. (2004): Risk Reduction Actions for Substandard or Impaired Tailings Facilities. Report of the European RTD project TAILSAFE, http://www.tailsafe.com/, 29 p.

Kreft-Burman, K., Saarela, J. & Anderson, R. (2005): Tailings Management Facilities – Legislation, Authorisation, Management, Monitoring and Inspection Practices. Report of the European RTD project TAILSAFE, http://www.tailsafe.com/, 66 p.

Niederleithinger, E., Kruschwitz, S. & Martin, T. (2005): Non-Destructive and Minimally Intrusive Methods for the Investigation and Monitoring of Tailings Impoundments. Report of the European RTD project TAILSAFE, http://www.tailsafe.com/, 51 p.

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1 Introduction

1.1 Intervention

The objective of a tailings facility is to provide safe storage of ground waste rock and process chemical constituents whilst having a minimal impact on the surrounding environment. Risk reduction plays a key role in the design and construction of modern tailings impoundments to prevent failures from occurring. Intervention actions are implemented to reduce this risk and provide long term stability of an impoundment. Many techniques can be used, with both conventional and unconventional techniques having been discussed in this work package.

The need for intervention actions has come about due to the increase in the worlds environmental lobby, company polices, legislation, guidance documentation and from examples of tailings impoundment failures. Some of the world's worst tailings failures, in terms of life lost and environmental damage could have been averted if suitable management and maintenance programs had been established. The Los Frailes tailings impoundment failure caused huge environmental damage when over 6 Mm^3 of cyanide laced tailings poured into the Río Agrio, a tributary of the Río Guadiamar. Huge fish kills, 3,000 Ha of land destroyed and 5,000 jobs in agriculture were lost as a result of the failure. The clean up costs of the spill have already reached just over € 100 million.

There are many tailings impoundments around the world, both active and abandoned that are potentially unsafe and are deemed a hazard to the environment. Strengthening works are usually implemented or removal of tailings altogether is an option. Removal is a fairly new idea and has only come about due to improvements in processing technology (typically carbon-in-leach and carbon-in-pulp methods). Old tailings impoundments can be reworked and the tailings can be stored in a safer and better structurally engineered impoundment. In some instances the old tailings are simply moved to a safer location for environmental reasons. This is now starting to happen in areas where towns are adjacent to old tailings impoundments. Problems with water contamination and dust have caused government environmental bodies and environmental groups to make mining companies remove their waste to a more suitable location (e.g. South Africa, Australia, and Chile).

Intervention actions are helping to stabilise old impoundments and particularly help with preventing ground water contamination. Bentonite seepage walls are one example of strengthening techniques used to prevent environmental contamination from existing tailings facilities. Simple remediation of embankment slopes can help to prevent erosion and contamination of local water courses. For areas of high rainfall and weak embankment material geo-grids and networks can be used to help the stability and growth of vegetation.

1.2 Abandoned tailings impoundments

Once disposal to an impoundment ceases the size of the decent pond generally reduces resulting in a drop in the phreatic surface. As the continual supply of water to the impoundment has ceased the strength and stability increases over time. Once remediation techniques have been established the risk of failure of an impoundment is further reduced. Areas of high seismic activity and high levels of precipitation do however pose a risk to an abandoned tailings facility. If remediation techniques are not adequately implemented problems with overtopping, embankment erosion, and toe erosion can cause a failure to occur.

Details of the reclamation of a tailings impoundment are generally included in the planning stages of a mine venture. Government authorities make sure that mining companies remediate land after mine abandonment and hope to avoid long term environmental contamination. Less responsible mining companies from past years have scared the landscape causing an economic burden for governments.

Figure 1: Abandoned uranium tailings pond next to the Baltic Sea, Sillamäe, Estonia.

1.3 Legislation

Some countries in the developing world, and areas where environmental impacts are low (e.g. remote barren regions) there may be leniency in environmental legislation. Mining companies however well established they may be will sometimes try and save money rather than be environmentally cautious. One example of a tailings failure by such an established mining company happened in Guyana, South America. The Omai mine owned and operated by Camboir Inc., a Canadian mining company, had two minor and one major impoundment failure that released cyanide laced solution into the Omai River, a tributary of the Essequibo River. Cost cutting in the construction of the impoundment is the cause of the disaster that killed > 400 fish and left 80 km of river an environmental disaster zone.

The Omai tailings impoundment was built by Omai Gold Mines staff without proper equipment and materials. Figure 2 shows the poor construction and cracking in the embankment.

Figure 2: Poor construction of the Omai Dam (Source: http://www.tailings.info/).

After the failure the Guyana Government took Cambior to court for environmental misconduct but later dropped the charges and granted an extension to the mine which would create another 320 jobs. The government has a 4% share in the operations and the income the mine would bring is vital to their economy.

1.4 Equipment and technology

Tailings ponds built before the 1960s were constructed without proper geotechnical knowledge and the use of large mechanical equipment. It was not surprising that these old impoundments failed which sparked issues regarding the safety of tailings impoundments and their threat to the environment. Today, technology permits us to economically mine lower grade ores resulting in more waste and larger tailings impoundments. However, geotechnical knowledge has advanced due to slope stability and soil strength research over the last 30 - 40 years.

Mobile equipment has helped considerably with embankment construction and installation of drainage and strengthening technologies. Compaction and dewatering helps to reduce the risk of failure of an impoundment and is essential to all earth filled embankments. The large machinery we have today is capable of meeting the demand of high tonnage tailings disposal and raising of embankments. Figure 3 shows one of the many sheep's foot rollers compacting the L-L tailings dam at the Highland Valley Copper Mine in Canada. The embankment is currently 126 m high.

Figure 3: Mechanical compacting equipment.

Static and dynamic liquefaction events are still to this day misunderstood. Many impoundment failures have occurred from dynamic liquefaction events, some of these being created from mobile equipment. One example of this type of failure occurred at the Sullivan Mine in Kimberley, British Columbia. Motor scrapers that was being used to raise the impoundment were traveling along the dyke crest disposing of material and then returning past the dyke toe for reloading. A dynamic induced liquefaction event occurred causing a rotational slump of part of the dyke being raised. Fortunately no tailings escaped.

2 Evacuation of tailings pond content, in whole or part, by digging, dredging, pumping, breaching

2.1 Introduction

Identification of mineral resources, exploitation, mineral processing and handling of residuals are all within the frame of mining operations. Today, mineral processing techniques have advanced to treat low grade ores and now old waste rock piles can be reprocessed to reclaim valuable materials. Parallel to this tendency, the changing of technical, ecological and legislation conditions might make it necessary to reuse materials once handled as a tailing due to environmental, safety or land management reasons. Tailings, the waste materials from mining operations are:

- Waste rock
- Waste rock mixed with useful minerals
- Residuals of mineral processing,
    - Residuals of physical-mechanical mineral processing methods
        - Contaminated by the preparation technology
        - Not contaminated by the preparation technology
    - Residuals of chemical mineral processing methods
        - Contaminated tailings
        - Chemically evolved tailings
        - Pure tailings
- Materials that are not economically viable.

Classification is important, because information can be gathered about safety classification of tailings in accordance to environmental and waste management strategies. It is also important to examine the mined mineral too, because sometimes, dangerous components evolve from these minerals. There is also the concern of handling mine waters and solved materials, especially where heavy metals are involved. Tailings can be found in the form of: solid, suspension and liquid.

Storage of tailings can be:

- Former mines (open pit and underground)
- Surface and underground storage piles
- Tailings pond

Properties of the suspension state tailings are usually not permanent as suspension settles and becomes consolidated over time. This settlement occurs faster near the surface and plastic suspended state could generally exist at greater depths. Liquid states are usual in tailings ponds, both during and after the impoundment operation stage. Precipitation can affect the water balance of a tailings pond and can increase safety and environmental risks of tailings facilities.

Treatment of waste rock piles could be different during and after a mining operation:

- Simple placement
- Technical recultivation without biological installation
- Full recultivation with agricultural or forestry usage
- Sale

Evacuation of waste rock piles and tailing facilities might become important for different reasons:

- Partial or complete re-use
- Environmental legislation, elimination or reducing environmental pollution
- Reaching of safety needs
- Landscape or land management
- Handling of tailings

The chosen methods of evacuation are determined by the aggregate, mixture state, storage, transportation possibilities, further handling and use of the tailings. Evacuation methods and equipment are discussed in the following sections.

2.2 Hydraulic methods

Exploitation of tailings can be effective by hydraulic methods if conditions are suitable. Hydro mechanisation has many advantages compared with mechanical dry exploitation, such as simplicity, efficiency and cost effectiveness. The main conditions are the following:

- Geological properties
- Climate
- Physical-mechanical properties of the tailing such as,
    - Density, porosity
    - Moisture content
    - Shear strength and plasticity

Hydraulic exploitation is done by a high pressure water jet distributed by a hydro-monitor. Hydro-monitors can be classified by the diameter of the water jet and the pressure of the water.

Table 1: Hydro-monitor pressure comparisons.

Type of hydro-monitor	**Pressure [Pa]**	**Diameter of WB [mm]**
Low pressured	$< 10^6$	50-150
Medium pressured	$10^6 – 6 \times 10^6$	15-30
High pressured	$6 \times 10^6 – 25 \times 10^6$	1-5
Super high pressured	25×10^7	<1

Low pressured hydro-monitors are primarily used for tailings exploitation. Three different zones and parts can be established in the water jet after it leaves the nozzle of the hydro-monitor. Zones are describing the cross section of the jet, and parts are delimiting the jet in length where zones are changing.

First zone: The jet is almost a continuous core. Compactness of the water jet is the highest.

Second zone: Compactness of the jet is decreased and contains air bubbles.

Third zone: Jet is divided into more small jets and strongly filled with air.

First part, where first zone is dominant has the most notable usability. The main parameters of this first part are: length of starting part, axial velocity and pressure of the water jet.

The *length of starting part* is determined by the following:

$$\frac{1_{vl}}{d_f} = A_v - B_v \cdot R_e$$

Where R_e is the Reynolds number of the water jet leaving the monitor tube.

$$R_e = \frac{V_{va} \cdot d_f}{\nu}$$

where:

l_{vl} is the length of the starting part, m

d_f is the diameter of the nozzle, m

V_{va} is the velocity of the water jet at the leaving point, m/s

ν is the kinetical viscosity of water, m^2/s

A_v and B_v are experienced values depends on the properties of hydro-monitors

The axial pressure of the water in different parts can be determined by:

$$\frac{P_{v1}}{P_{va}} = (\frac{l_{v1}}{l_v})^k$$

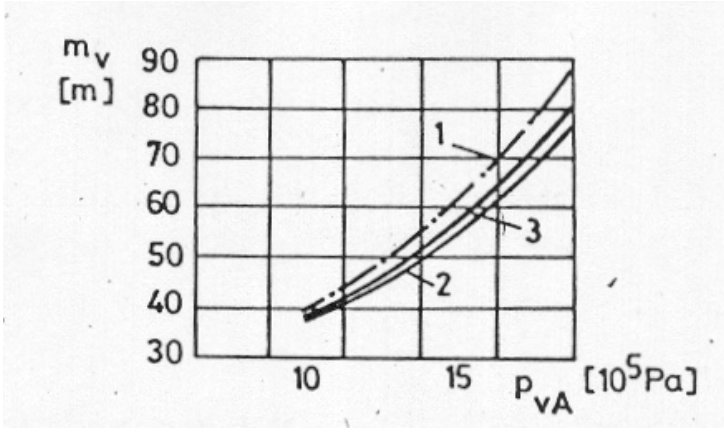
where:

P_{vA} is the dynamic axial pressure at the nozzle, Pa

P_{v1} is the axial pressure in distance l_v (m) from the nozzle, Pa

k is an empirical value dependent of the flow properties of the water

Figure 4 shows how the water jet is extend. Using this figure, the angle α_v can be determined which determines the compactness of the jet.



1. 0-10 m water jet range
2. 10-20 m water jet range
3. average value

Figure 4: m_v as a function of dynamic axial pressure [65].

$$tg\frac{\alpha_v}{2} = \frac{D_v - d_f}{2l_v}$$

where D_v is the diameter of the water jet in l_v distance from the nozzle.

When the water jet impacts onto the rock and tailings it is exploiting their properties due to different effects. One of these is the washing ability of the water flowing downwards and moving tailing particles adjacent to each other. Rising capillary pressure in the tailings is the second effect which causes changes in the physical-mechanical properties of the tailings. This causes a decrease in the shear strength. When the water jet impacts onto the front surface, mechanical forces increase. The measure of these forces depends on the impact angle of the jet and the shape of the exposed surface (Figure 5).

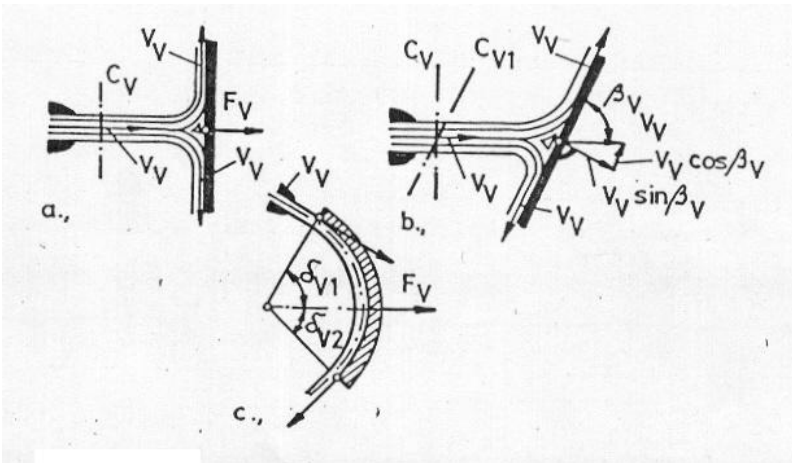


Figure 5: Effect of water jet for the surface depend on its impact angle [65].

Table 2: Action forces of the water jet on the impact surface.

Action force when perpendicular to the front	$F_v=\rho_v \times C_v \times V^2_v$
Action force in β_v slope angle	$F_v=\rho_v \times C_v \times V_v \times \sin\beta_v$
Action force in arc shaped slope with given angles (δ_{v1} and δ_{v2})	$F_v=\rho_v \times C_v \times V_v \times (\sin\delta_{v1}+ \sin\delta_{v2})$

Where:

ρ_v is the density of water, Kg/m^3

V_v is the flow volume of the water, m^3/s

C_v is the cross-section surface of the water jet at the place of exploit, m^2

V^v is the velocity of the water jet, m/s

Gravity also can work for exploitation if the so called ‘under slotting’ method is used.

2.2.1. Equipment of hydraulic evacuation of tailings

The main equipment is a hydro-monitor, which is able to covert potential energy of water into kinetic energy. Hydro-monitors can be classified by the control method of the water jet:

- Controlled by hand
- Remote controlled

Hydro-monitors are specific to various applications and can be portable and self-moving, as well as specific to close and long-ranged needs. Soft rocks, like tailings can be exploited by long-ranged, low-pressured hydro-monitors are possible to operate with 15-50 m/s water jets with compact shape. They can focus the jet to anywhere in the front without moving. Schematic pictures of hydro-monitors can be seen in Figure 6.

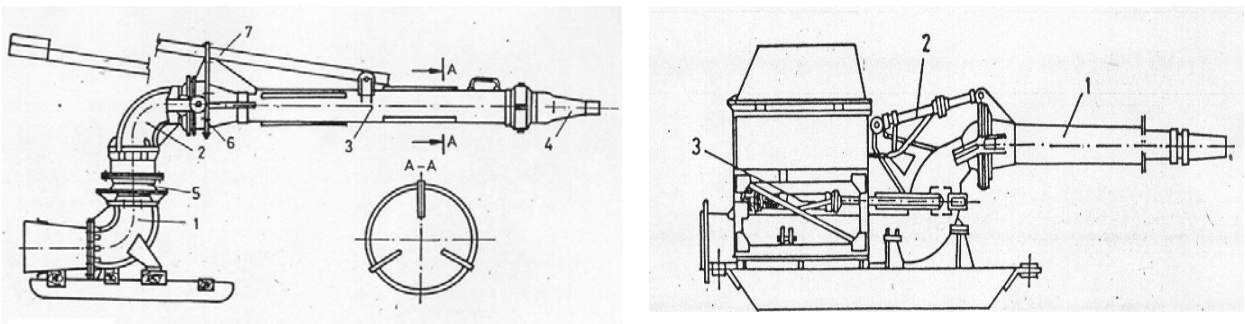


Figure 6: A human and a remote controlled hydro-monitor [65].

The length of the nozzle can be 2.5 - 3 × d_f where d_f is usually 30-800 mm. This varies depending on the direction of the water beam, and the direction of the slurry. Four main exploitation scenarios can be described.

Water jet and flow out is in the same direction, exploitation from the top. The hydro-monitor is on top of the material that is being evacuated. The slurry flows in the direction of the water jet in a special trench. Advantages of this method are that the monitor and pipeline are on a dry surface, which enables to operate and carry them easily. One disadvantage is that the water jet impacts onto the material at a sharp angle, dropping the efficiency of the exploitation (Figure 7 a)

Water jet and flow out is not in the same direction, exploitation from the top. This method is used rarely, because it is necessary to dig the trench in the whole cross-section to the entire depth prior to excavation (Figure 7 b).

Water jet and flow out is in the same direction, exploitation from the bottom. This is a similar method to the previous one but is more effective, because of the angle of jet impact (Figure 7 c).

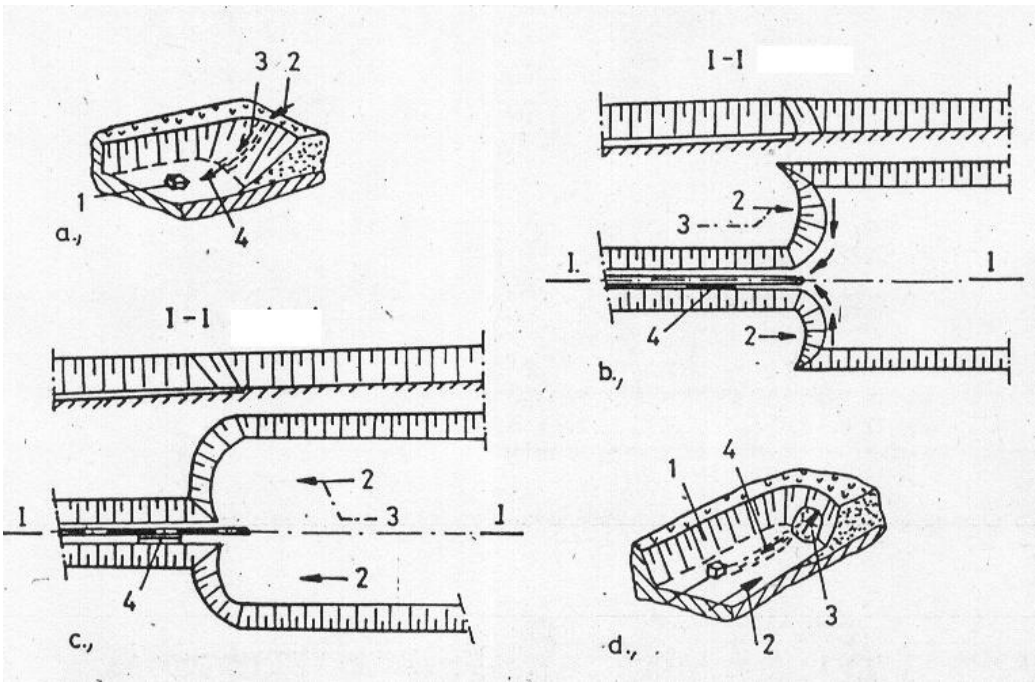


Figure 7: The four exploitation schema [65].

Water jet and flow out is not in the same direction, exploitation from the bottom. This is the most common exploitation method. One key advantage to this method is that there is no need to prepare the area in detail prior to extraction. Exploitation efficiency increases, because the angle is close to the optimal 90° and the so called under slotting technique can also be utilised. Disadvantages are the difficult working conditions and constant monitoring of the flow path of the slurry to prevent migration. If the slope is high, safety distance from the slope can be longer than it was necessary for optimal placing of the monitor itself.

Design of the water support pipelines of the monitors is done by general hydraulic computing. It is based on the tailing properties, planned technology, necessary performance to determine the necessary water pressure, specific amount of water for use and total water need. It can be noted that only the first and second zone can be used for exploitation, therefore the only 20-30% of total range of the monitor can be used.

2.2.2. Underwater evacuation methods of tailings

Sometimes, tailings are deposited and stored underwater. Underwater exploitation should be used if dewatering of a tailings pond is not possible for any reason. In this case it seems to be practical to use floating equipment able to excavate solid material from high depths and able to elevate material to the waters surface. Underwater exploitation can be operated by mechanical, hydraulic, hydro-pneumatic and combined methods. Mechanical excavators can be used on an intermittent or continuous basis, whereas hydraulic, hydro-pneumatic and combined methods are always used on a continuous operation. Intermittent-duty excavators might use swinging jig, racks with travelling crabs and a slewing crane.

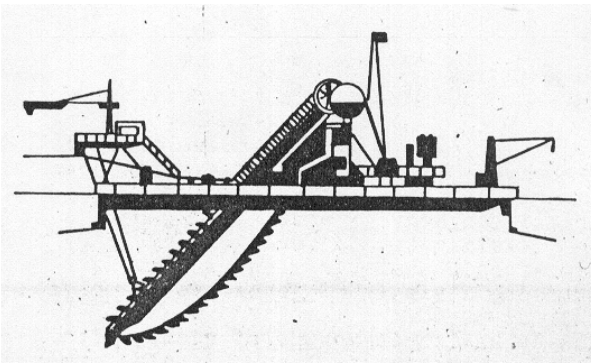


Figure 8: Bucket line floating grabbers (Source: http://www.tmd.ihcholland.com/).

All three methods use grabber heads to operate. After grabbing the solid from the bottom of the pond, it is necessary to emptying the grabber head. It can be unloaded onto a truck with the slewing crane method, or can be conveyed, or a combination of both methods. It is also necessary to dewatering the solid material which ever method is used. Continuous duty mechanical floating equipment might be bucket-ladder grabbers or cutting roller grabbers. Operation depth can be up to 20 m for these machines. Cutting roller grabbers (Figure 9) are able to exploit hardened and heavily consolidated tailings. Transportation of the exploited solid material is hydraulic.

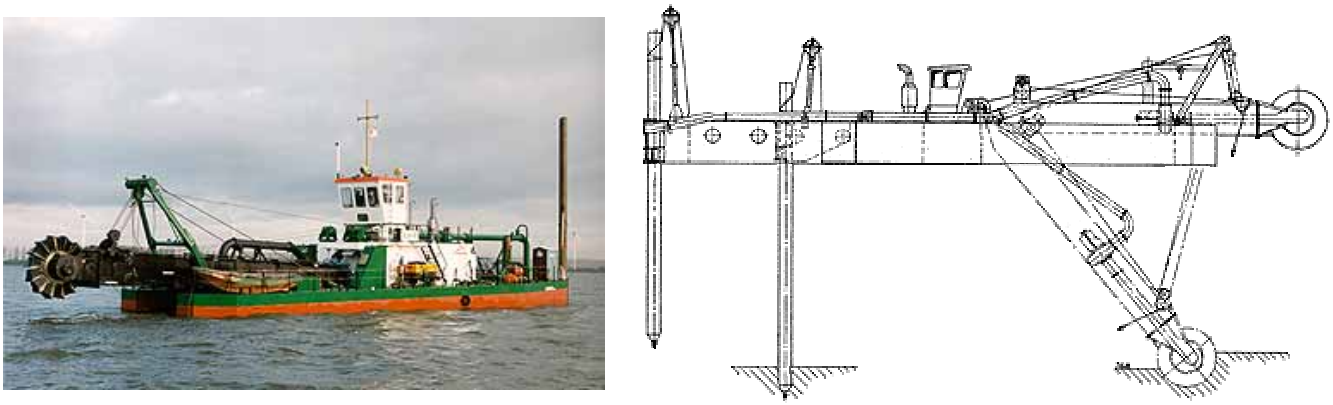


Figure 9: Cutting roller floating grabbers (Source: http://www.tmd.ihcholland.com/).

The simplest hydraulic floating grabber operates by suction. Over washing velocity of the flowing water is dependent on the particle size distribution of the solids evacuated, the density of the solids, hardness of the solids and of course the performance and vacuum generated by the grabber.

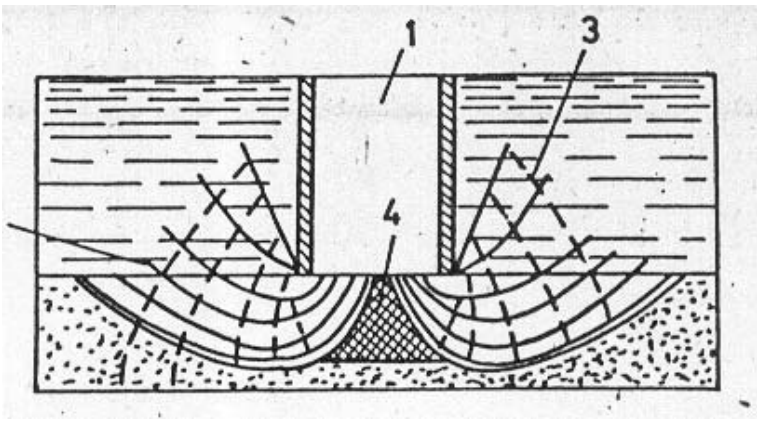


Figure 10: Hydraulic sucking tube and as it works [65].

The suction area arises around the sucking pipe, where tailing particles are breaking away from the bottom and going into the sucking tool with the water. The intensity of this is dependent on the distance between the tube and the tailings surface, the shape of the tube end, sucking velocity, and physical-mechanical properties of the tailings. This method is well applicable for fine slurries.

Hydraulic floating grabbers with jet pumps can also be applied. This equipment operates with a high pressure water jet generated by the floating trail or a pump located at the edge of the pond. Jet pumps are used to exploit the tailings and also to transport it back to the surface through pipelines.

Figure 11: Floating grabber with a sucking tube equipped with a mechanical exploiting head (Source: http://www.tmd.ihcholland.com/).

A ***hydro-pneumatic floating grabber*** operates with an improved mammoth piston pump and a producing pipe. Exploitation of the tailings particles is done by a high-pressure water nozzle. Transportation of the particles is done by a mammoth piston pump in the producing pipe.

2.3 Evacuation of tailings by mechanical dry technologies

Evacuation of tailings by dry mechanical methods could be open pit mining operations, methods and processes together. The basis of this should be the principals of mining experiences, mining equipment and the special properties of the tailings itself. The extraction technologies are usually consisting of exploiting, loading and transportation. These three work phases are sometimes hard to separate, which is why this report summarises open pit mining methods and their equipment regarding to tailings exploitation.

In mining operations, the rock properties will determine which extraction method is most suitable. If we determine tailings as a kind of rock, we find that it is mostly soft disturbed “rock” with high moisture content. Furthermore it makes the extraction more complex if tailings are contaminated with different types of chemical additives (cyanide, flotation reagents, hydro-carbons). When working with these materials, labour and environmental safety question arises which have been reviewed in chapter 3 of this workpackage. In addition when planning extraction it should also consider economical issues rather than how economically or environmentally important exploitation is. Before describing the machines and equipment of dry evacuation it is important to note that it is always necessary to dewater the tailings facility and eliminate open water tables before mechanical methods are used, or evacuation should be done by underwater excavation methods instead. Conventional high performance pumps can be used to pump out water. This is a necessary and useful step to reduce dam strain.

2.3.1. Classification of exploiting machines

Mainly we can classify mining equipment by its operation time:

- Mining equipment with continuous operation
- Mining equipment with periodic operation

Machinery taken from the first class can not be used for tailings evacuation purposes, because these machines are very heavy and difficult to operate on a tailing pond. In the case of the tailings itself being very dry with little or no moisture content, there is a possibility of exploiting the tailing facility by opening the embankment. However, this rarely occurs, and if it happens, it is very hard to move a ladder bucket dredger into the spot, due to its geometrical dimensions, its

weight and speed. From another point of view, if it is not a close catastrophic situation, this action is not really cost efficient.

Machinery taken from the second class has higher feasibility to operate as a “tailing evacuator”. These machines don’t have such a high weight and large geometric size thus making them suitable for tailings evacuation. The low ground pressure allows this type of machinery to operate on top of the tailings pond, and in special conditions where the tailings have lost their moisture and reached a potential stability which is able to support the machines. If this cannot be reached, some of these machines can work from the embankment of the tailing facility with high efficiency. Another innovative possibility is to evacuate soft tailings with high water content by a grabber or dredger attached onto a floating pad. Transportation of this pad onto the pond surface can be carried out by a hovercraft which can install the pad anywhere. These tools and tailings carriage could be similar as it is used in dredging-boats for underwater exploiting.

2.3.2. Evacuation with single bucket dredgers

Periodic dredgers have a four part working cycle for operation. Exploiting, recourse, evacuation and return back to exploit. This cycle can combine exploitation and loading, therefore we need only transporting equipment to transport evacuated tailings into its new place. Single bucket dredgers are very popular in many areas of tailings excavation. This results in a high variety of available machines with high efficiency, reliability and also continuous improvements to make them of higher capacity. Bucket volumes can reach up to 160-170 m^3.

This class of machine can also consist of many different machines, such as grabbers, revolving excavators, slack line excavators, trencher excavators. Different types of drives make them able to reach their point of operation such as walking drives, caterpillars, wheels and can also be travelling on rails. Dredgers with fixed buckets use cables (or chains) or hydraulic actuation to operate their bucket in a forced line/orbit.

2.3.3. Slack line excavators (dragline)

A schematic drawing of a slack line excavator can be seen in Figure 12. Main parts of the dredger are bucket (1), jib (2), cables (3-5), revolving upper part (6) with the operators desk and engines, and the drives (7). Drives are usually caterpillar or walking drives.

Loading of the bucket is carried out between the I and II part of the operation. Then the bucket is raised and the upper part of the dredger is revolving into evacuation position. To loosen the dragging cable the bucket turns face down and evacuation occurs (see in position III). The

excavator turns back to exploiting position (I) and releases the bucket again to load it. If the drag cable is strained until it is released and in this moment this cable is suddenly loosed, the bucket might reach point IV and the radius of exploitation can be increased. The bucket volume can be up to 80 m^3 and the length of the jib can be up to 125 m.

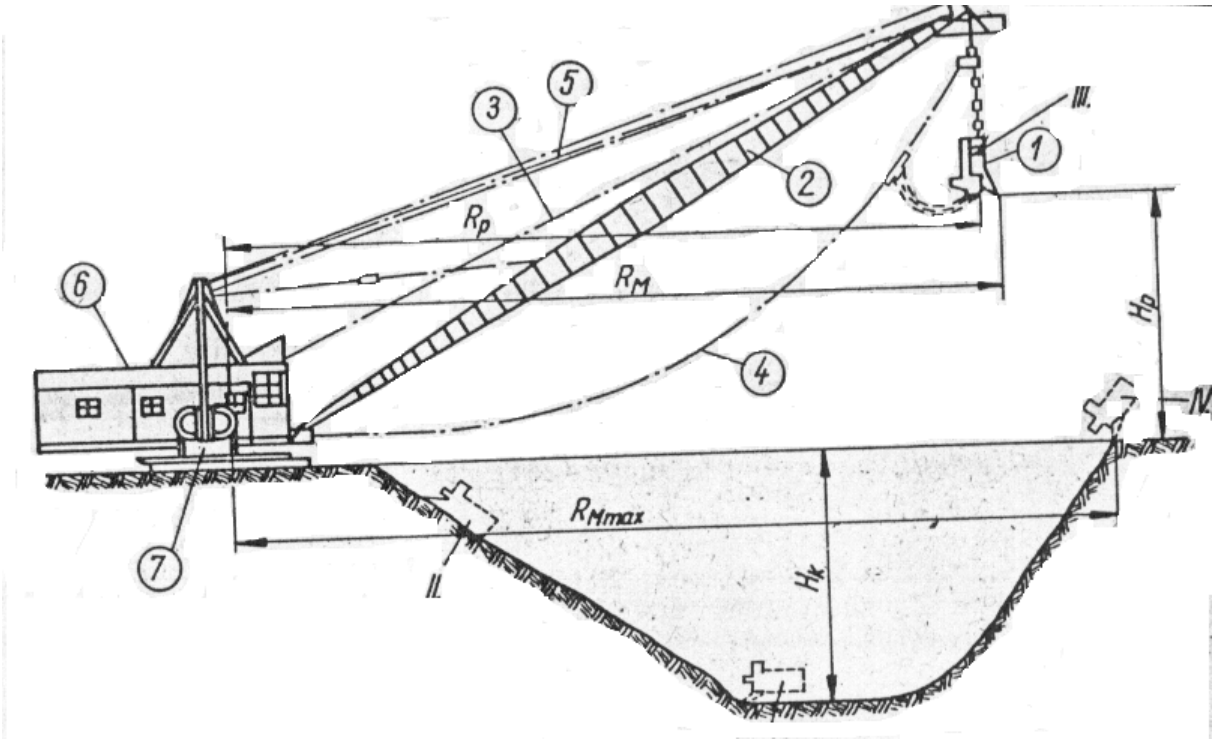


Figure 12: Schematic draw of a slack line excavators [65].

2.3.4. Trencher excavators

These machines are primarily used for trenching. They are applicable for tailings evacuation from embankment or pontoon to load material directly into trucks.

The bucket of trenchers could be closed or equipped with a “door” at the bottom of the bucket to make the evacuation easier. These machines use cable or hydraulic motion to operate. A schematic drawing of a trencher using hydraulic valves for actuation to operate their bucket can be seen in Figure 13. Loading of the bucket occurs when it is moving from point I to point II. Then the bucket is raised and the upper part of the machine is revolving into evacuation position. The bucket has to turn into position IV for evacuation. The excavator turns back to exploiting position after evacuation and starts the cycle again.

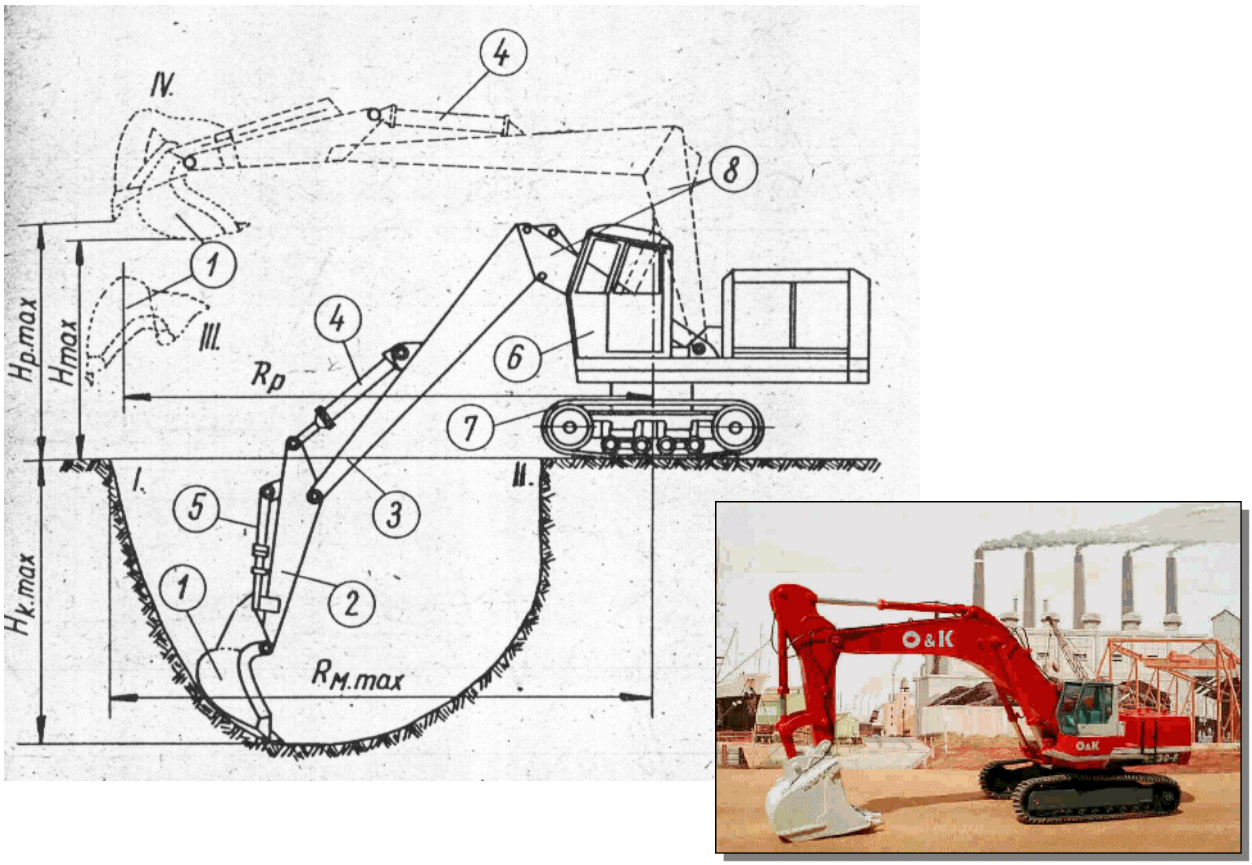


Figure 13: A schematic draw of a trencher using hydraulic valves for actuation to operate their bucket (Source: [65] and http://www.orenstein-koppel.com/).

2.3.5. Grabbers

Excavators with revolving upper parts can be equipped with a grabber head instead of buckets. Grabber heads uses 2 up to 8 grabber jaws. Excavators usually use 2 jawed grabbers equipped with teeth for easier penetration into the soil or exploited material. A grabber-head can be seen in Figure 14. It is operating as follows: The grabber head is lowered to the surface in open phase. Loading occurs while the grabber heads are closed by cable or hydraulic cylinders. Loading is happening because of the effect of the weight of the grabber head or it can be helped to load by hydraulic cylinders. When the grabber head is full with tailings it is positioned to the point of evacuation. This can be a truck or a belt conveyor.

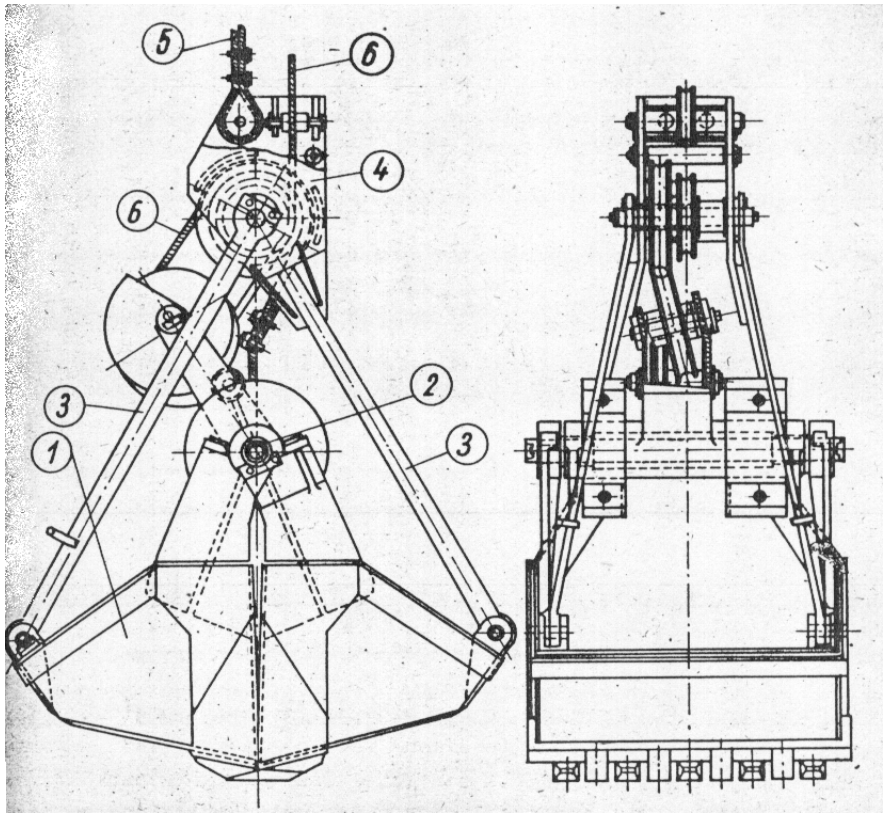


Figure 14: A grabber-head [65].

2.4 Breaching

An unexpected tailings impoundment breach can have disastrous impacts on the surrounding environment. This has been seen in many countries around the world where not only the natural environment is impacted, but people have lost their lives. The problem is that when a breach occurs, some or all of the tailings migrate out of the impoundment and flow downstream. Any obstruction in the path of the flow is either swamped in slimes or is carried with the flow further downstream. A good example of a disastrous flow of tailings as a result of an impoundment failure occurred in 1985 at the Prestavel mine in Stava, Italy (see Figure 15 and Figure 16). The impoundment breached as a result of heavy rains which caused overtopping. The flow travelled down the valley through the town of Stava killing 268 and destroying 62 buildings and 8 bridges [114].

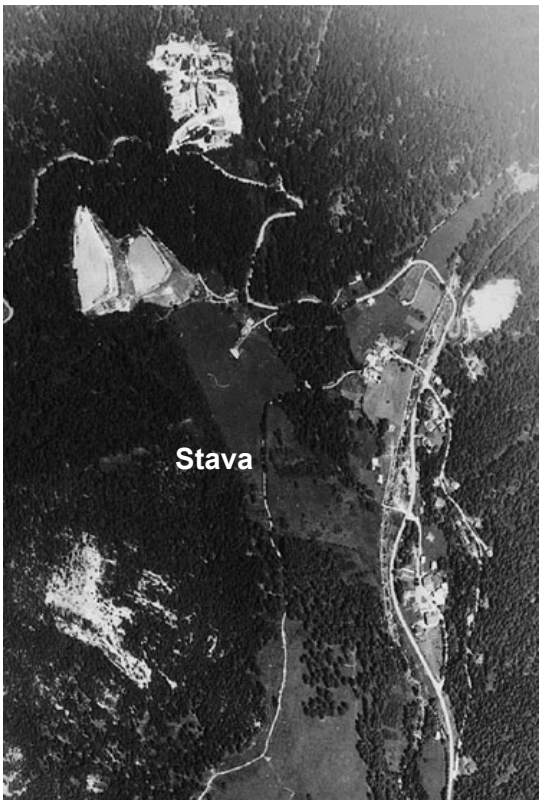


Figure 15: Stava before the breach (Source: http://www.wise-uranium.org/mdafst.html).

Figure 16: Stava as the tailings travelled through the valley (Source: http://www.wise-uranium.org/mdafst.html).

2.4.1. Flow characteristics of tailings

If a failure of an impoundment occurs, the scale of destruction as a result of the tailings migrating out of the impoundment is widely influenced by the water content and particle size. Poor consolidation with high water content increases the risk of failure and potential environmental impact as the shear strength of the tailings in the impoundment is very low. The flow of tailings migrating out of the impoundment will continue until they gain enough strength to resist flowing. Land topography, obstructions, and weather conditions play an important role in hindering or assisting tailings flow.

2.4.2. Deliberate breaching

Tailings in impoundments can be removed in the conventional ways by digging and dredging, however breaching a part of the embankment is an alternative. The consolidation of tailings and water content of the impoundment will determine the flow characteristics of the tailings, and the volume of tailings that migrate out of the impoundment.

Deliberately breaching an impoundment carries a high risk of environmental damage as the exact consequences of breaching are never known until the breach has occurred and the tailings remain static. For this reason, breaching an impoundment is very rarely used. However, abandoned gold and uranium tailings impoundments have been hydraulically mined by breaching the outer embankment.

2.4.3. Hydraulic mining

Hydraulic mining monitors used today were first developed back in the early sixties by English China Clays, Cornwall, England. The technology has been used on soft rock applications and on old tailings dams to either move or reprocess the waste. The monitor uses high pressure water to erode the tailings in sections, washing the material downstream which is collected in a sump. Tailings dams are generally segregated by the coarseness of the material (coarse fraction near the spigot) and if a particular area of a dam is too coarse for pumping then blending is required. Once the required density is obtained in the sump and screening has prevented large objects the slurry is then pumped to thickeners and the underflow is reprocessed in the plant. The tailings are then stored in a tailings impoundment [23]. A typical flow sheet for the reprocessing of tailings is shown in Figure 17.

It can be noted that the use of hydraulic mining for tailings can be to either reprocess the waste, mine the waste as a product, or for moving of the tailings to a more suitable location.

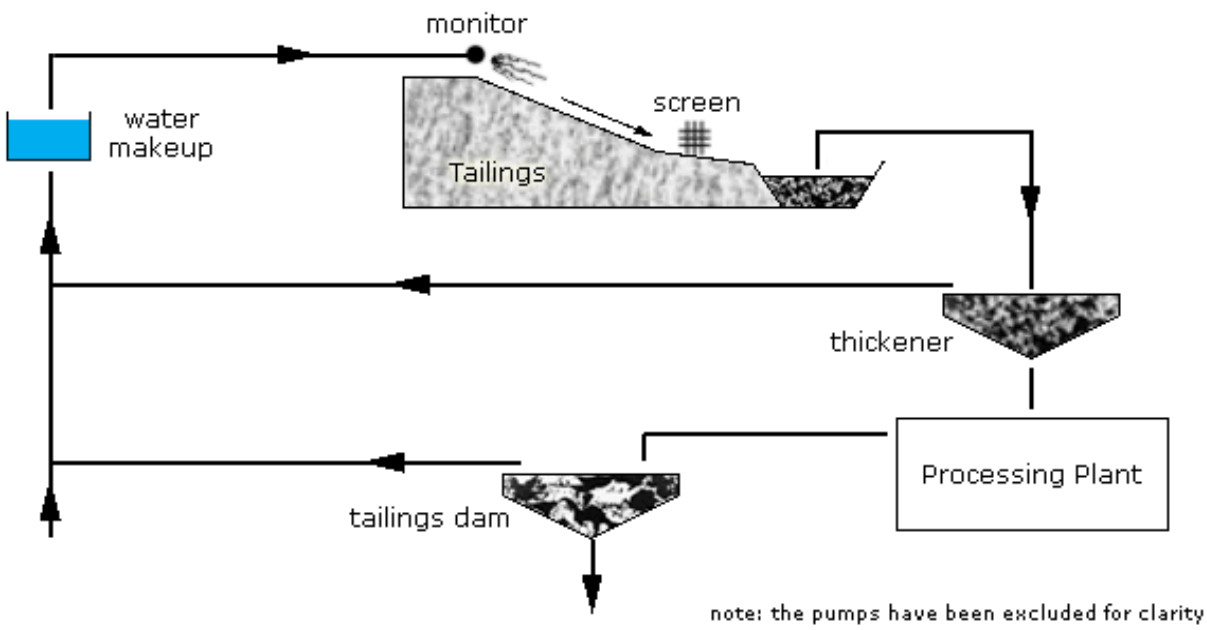


Figure 17: Hydraulic mining of tailings.

Figure 18: Hydraulic mining of a tailings dam (Fraser Alexander Ltd).

Figure 19: Cutting into the tailings (Fraser Alexander Ltd).

Figure 20: Aerial view of a hydraulically mined tailings dam (Golder Associates).

Some tailings impoundments are hydraulically mined to not just process the tailings but to re-site them for environmental reasons. This is an affective method and can take a shorter time than mechanical excavation, depending on the density and particle sizes of the tailings.

2.4.4. Deliberate breaching – short case studies

Disputada Mine, Chile

The mine has three tailings dams that need to be moved for environmental reasons. Two of these deposits are located in a steep narrow valley with the third deposit being located on the side of a valley.

The use of hydraulic monitors is considered as the only economical option as blending of the coarse fraction with the middlings and fines allows pumping of the tailings. However, the tailings are mixed with rock deposited during the construction of the impoundment and subsequent impoundment division to form road ways. A small amount of rock has deposited from avalanche scree from the steep valley sides. The rock will have to be removed by mechanical methods that have to work in dry conditions. This poses a problem for the hydraulic operation which can be solved by having two mining areas to allow mining, drying and then rock removal. Dredging of

the material in the dams would cause damage to the mechanical equipment and pumps, also dry load and haul is considerably more expensive than hydraulic mining.

A production rate of 19,000 tonnes/day over an 8 month annual cycle is required to make the operation a success. Mining during the winter months poses hazards from avalanches, blizzards and freezing of pipelines and mechanical equipment [23].

During the mining operation the screened material is then pumped to a header tank almost 5km away at a height elevation of 200 m. From the header tank the tailings are gravitational fed to a new tailings impoundment 50 km away.

In the future mining of the saturated zone will pose a great challenge. Early indications show that floating equipment should be used to prevent a liquefaction event from occurring and risking the lives of the operators.

Figure 21: Mining into the unsaturated zone (AngloAmerican Chile & Fraser Alexander Ltd).

Figure 22: Mining the unsaturated zone further upstream (AngloAmerican Chile & Fraser Alexander Ltd).

Kaltails project, Kalgoorlie, Western Australia

The Kaltails project was established to reprocess and move tailings dumps from the Boulder and Lakewood areas of the city of Kalgoorlie. The operations ceased in September 1999 and had been ongoing for just over a decade. The tailings dumps were hydraulically mined, reprocessed and stored in an engineered impoundment located 10 km south east of Kalgoorlie. From the 60 million tonnes of tailings mined 695,000 ounces of gold was recovered by Carbon-in-Circuit (CIC) and Carbon-in-Pulp (CIP) leach and absorption circuits [60, 81].

Of the 333 hectares of land that was hydraulically mined, 262 hectares will be used for waste rock storage from the Kalgoorlie Consolidated Gold Mines (KCGM) superpit. The remaining 71 hectares have been contoured, seeded and revegetated.

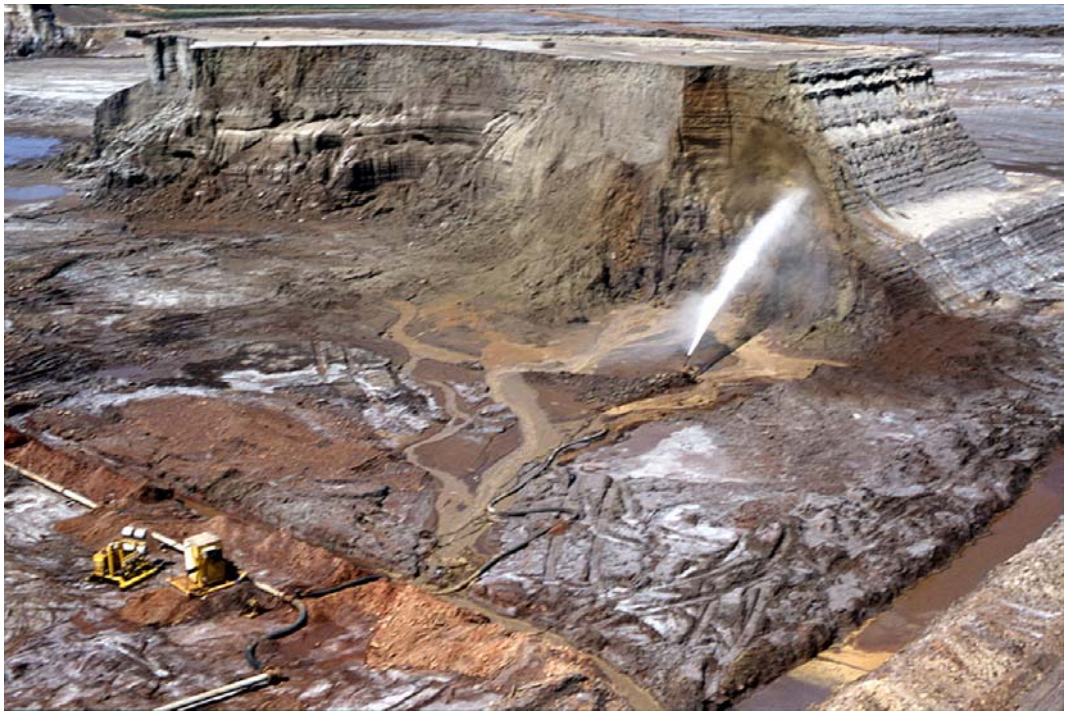


Figure 23: Remaining part of a waste dump being hydraulically mined (Newmont Mining).

Figure 24: A view from outside of the waste dump where a monitor internally erodes the embankment (Newmont Mining).

2.4.5. Accidental breaching – short case studies

Mufulira Mine, Zambia

On the 25th September 1970 an underground breach of a tailings dam occurred at the Mufulira Mine in Zambia. As the night shift crew were on duty the tailings dam above them collapsed causing nearly 1 million tonnes of tailings to fill the mine workings killing 89 miners [80]. A sinkhole opened on the surface allowing surface water to continue to pour into the workings (Figure 25 and Figure 26).

Figure 25: Sinkhole and processing plant (Source: http://www.tailings.info).

Figure 26: Aerial of the sinkhole (Source: http://www.tailings.info).

Los Frailes, Aznalcóllar, Spain

On the 25th April 1998 a tailings dam failed at the Los Frailes mine in Aznalcóllar, Spain. The failure is thought to have occurred as a result of the marl foundations of the dam being eroded by the acid seepage from the tailings that passed through the embankment walls. The weakness in the foundations combined with the minimal length of beach (ponded water encroaching the embankment) caused high stress in the foundations, thus resulting in the failure of the embankment material (Figure 27). In total, 4.6 million cubic metres of toxic tailings and effluent poured into the Río Agrio and Río Guadiamar Rivers.

Figure 27: Aerial of the breached embankment (Source: http://www.tailings.info).

Merriespruit, Virginia, South Africa

On the 22nd February 1994 the Merriespruit tailings dam overtopped from heavy rains causing a flowslide (static liquefaction) of part of the embankment (Figure 28). The reason for the failure was due to poor management of the freeboard and ponded water within the impoundment. The failure allowed 500,000 m^3 of tailings to flow out of the impoundment where they eventually stopped 2 km away in the town of Merriespruit. 17 people were killed and scores of houses were demolished [42].

The 31 m high impoundment had problems prior to the failure. Small slips had caused the impoundment to close temporarily, and only mine water with small amounts of tailings were deposited. This deposition of tailings caused the ponded water to move to the opposite side of the impoundment rendering the decant system useless. A satellite recorded the transition stages of the decant pond relocation as more tailings were deposited with the mine water. Heavy rains that fell on the day of the failure (30 - 55 m in 30 mins) caused the overtopping [54].

Figure 28: Aerial of the embankment breach (Source: http://www.tailings.info).

3 Treatment of tailings ponds in situ, including dewatering, by chemical or other means

3.1 Introduction

The objective of this section is the identification of treatment options for the body of fines within the tailings pond or the tailings pond content for dangerous or impaired facilities.

Though the tailings pond's design life is effectively perpetuity, which means to be able to survive in a stable form without human interventions, there are parameters that threat its stability. Its design should also address post closure issues such as long-term geotechnical stability of the impoundment, chemical stability of the tailings, long-term surface and ground water management and restoration (BPEMM, Tailings Containment). The above issues seem to be also the causes for the need of intervention actions, as they may compile the general characteristics of an impaired or dangerous facility.

The types of tailings that can be potentially treated *in situ* include those that carry such characteristics and properties that make the body of a tailings dam impaired or dangerous. The main properties that can pose such threat in an operating tailings management facility include the water content and the acid generating capacity of the tailings.

The water content of the tailings is generally associated with the applied deposition method. Mechanical means are used for reducing water content to required values prior to disposal, where chemical additives such as flocculants may be used to enhance settlement rates of solids. Consolidation of tailings upon deposition is dependent on the disposal method used, the point of discharge indicating thus the dewatering process of the tailings followed within the pond. In-situ dewatering may be improved by using mechanical means like decant towers, barge pumps etc.

Acid generating capacity reflects primarily the presence and generation of acid drainage (AMD) as a result of the natural oxidation of sulphide materials present within the tailings. AMD generation involves a complex series of interrelated reactions that take place either chemically or through microbially assisted mechanisms and depend upon the activity of bacteria and solution pH and Eh. *In situ* treatment of these types of tailings within an operating impaired pond can comprise techniques aiming at the addition of alkalinity, improvement of the physical stability and inhibition of bacteria action; these actions finally prevent AMD production. Amelioration of the geotechnical properties of the tailings in order to support vegetation generally after close-out can also be practiced, considering its implementation more likely within the last few years of operation of the dam.

3.2 Dewatering

Most common sources of threat and failure of a tailings dam that have been quoted by several authors are related to the forces of water [34]. Virtually all failures of tailings storage facilities between 1980 and 1996 occurred as a direct result of water actions and forces [17], whether they implicate seepage and internal erosion of the containment or overtopping due to blockage or inadequate capacity of decant or spillway systems. Water content thus and especially large quantities of stored water constitute a critical factor to the integrity of the body of a tailings dam.

Robertson [95] indicated that tailings impoundments are constructed with four primary objectives:

- To serve as a liquid: solids separating basin in which the tailings settle out allowing the excess process water to be decanted
- To contain or control excess process water contained in the tailings pore spaces and in the surface pond until it is decanted or seeps away in a controlled manner
- To contain the tailings solids in the long term (including soluble contaminants) to a level consistent with environmental protection requirements
- To achieve the first two objectives at the lowest possible cost

In situ dewatering of a tailings pond is usually a treatment process that is accomplished by the use of mechanical means such as siphons, pumps, decant towers, etc. as presented in the following sections.

3.3 Dewatering by mechanical means

3.3.1. Drainage

Water content of the tailings and embankment materials plays an important role in the strength of the impoundment. If the embankment is saturated, i.e. it has a high phreatic surface then the risk of failure is increased. If a failure occurs and the tailings are also highly saturated then the distance the tailings will flow out of the impoundment increases due to the water content acting as a transporter. Good drainage can reduce the risk of failure and successfully lower the phreatic surface of the embankment(s).

Mechanical methods can be used to aid drainage or reduce the saturation of the tailings or embankment material. Chimney, finger, or blanket drains can be installed as well as mechanically engineered filters and liners.

3.3.2. Drainage zones

The drainage of an embankment or impoundment can be effectively and economically achieved by using drainage blankets, finger or chimney drains. This is shown in Figure 29 as the grey shaded areas within the embankments for the centreline and downstream designs.

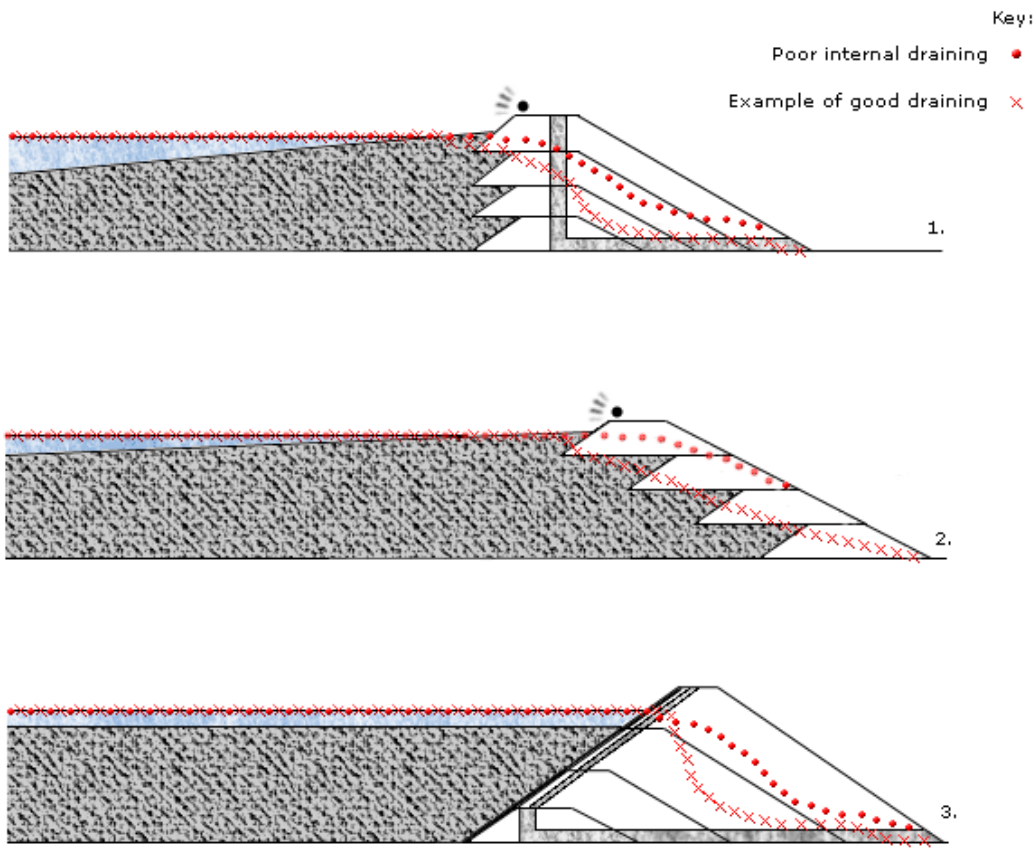


Figure 29: Drainage zones and phreatic surface levels.

Specific zones can be introduced within the dam wall or underneath the impoundment to aid drainage, and ultimately control the phreatic surface. The location of the drains should be sited depending on the rate of rise and the depositional techniques used. This is particularly important during the first cover of the drain(s) with tailings. To prevent blockages the tailings overlaying the drain should be cycloned close to the drain installation, allowing more control over the materials used and deposited.

All drainage zones in tailings dam construction need to be suited to the particular effluent and tailings characteristics. If for example seepage effluent has suspended particles then the drains may become blocked over time and render them useless. If coarse limestone is used for the drains and effluent of a low pH were to pass through, then erosion of the drains can cause instability of the dam wall, thus increasing the risk of failure.

Finger drains comprise of drain rock and coarse sand fraction encased in a geotextile filter surrounding a perforated pipe. Finger drains can be useful as you can to some respect control the direction of drainage better than a blanket drain, which is incorporated in the foundation of an entire embankment.

Downstream and centreline drainage

The downstream and centreline methods use both blanket and chimney drains to control the phreatic surface. The chimney drain is the vertical bed that runs down the centre of the impoundment wall, and the blanket drain runs along the base of the embankment. Generally, any chimney drains are connected to the blanket drains to aid the flow of seepage migration towards the toe of the dam wall.

Figure 30: Drainage blanket outlets with weirs at an embankment toe.

Upstream drainage

The upstream design will use just a blanket drain, unless the consolidated tailings are penetrated later during raising to incorporate a chimney zone. This is rare as upstream designs are not designed to contain large volumes of free water, and so the phreatic surface of the dam wall is generally low without the need for drainage zones.

For upstream embankments containing hazardous chemicals (e.g. cyanide) then a HDPE (geomembrane) liner maybe required. If this is the case a drainage blanket on the upstream side of the starter dyke incorporating an underdrain system is required (see Figure 31). Here, a perforated pipe runs through or underneath the starter dyke to the drainage blanket. The blanket generally consists of drain rock (10 - 30 mm gravel) encased in a geotextile material, which prevents sands and silts clogging the drainage rock, and ultimately causing a failure of the drainage system. This drainage system also reduces the head pressure on the geomembrane liner which can prevent leakage through defects [94, 25].

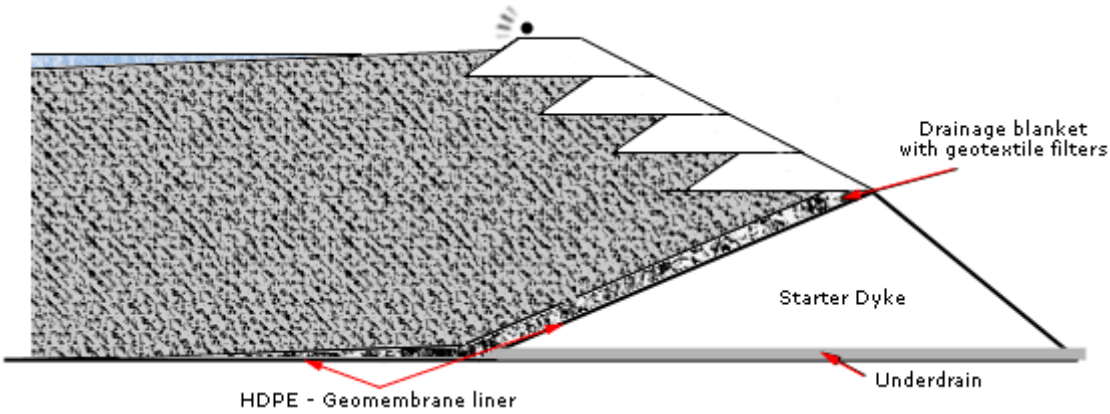


Figure 31: Upstream embankment incorporating a geomembrane liner.

3.3.3. Pumping

Conventional tailings impoundments contain free water that is normally situated away from any embankments in the centre of the impoundment. To prevent the free water submerging the beached tailings and encroaching the embankments pumping is required. Generally the volume of water contained in the tailings dam is dependent on the return water used in the processing plant. More water is stored in an impoundment that is located in an arid environment to allow the processing plant to operate during the dry seasons.

The free water is decanted using either decant towers which would have had to be installed in the impoundment during construction, or by using a floating barge with pumps attached (Figure 32).

3.3.4. Decant towers

Decant towers require a concrete conduit to be installed underneath the tailings and the embankment. As the volume of tailings deposited in the impoundment increases the decant tower will require raising. For some decant systems a simple screw or bolting together of pipe work is required, although some decant systems are raised and have the previous intake ports sealed to prevent tailings clogging the conduit.

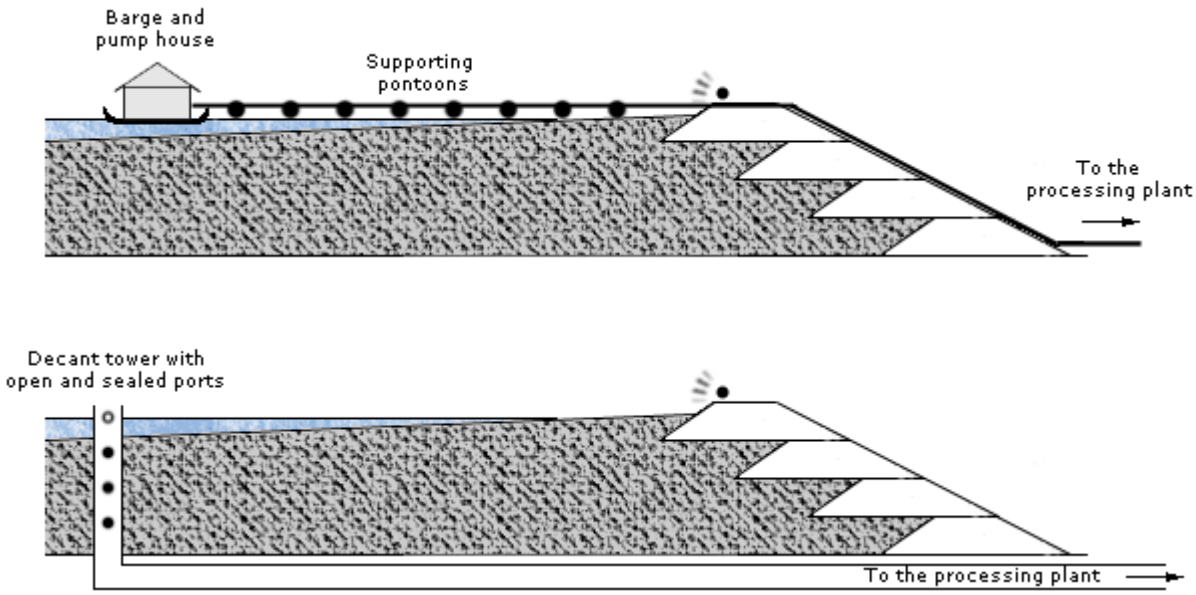


Figure 32: Floating barge and decant tower facilities.

Decant towers are not preferred for mill return water due to the vulnerability of the conduit to collapsing from the pressures of the increasing weight as the tailings are deposited. If a conduit does collapse the embankment may be susceptible to a piping related failure. The Stava tailings dam failure of 1985 occurred as a result of a decant tower collapsing [114].

Advantages of a decant system:

- Mechanical or electrical failures do not interrupt discharge.
- For a decommissioned pond they aid surface drainage and maintain a low pond level.
- Raising of the decant system is easy and cost effective.
- Low maintenance with only sporadic checks required.
- The greater the head of water over the decant system (e.g. storm conditions) the greater the discharge capacity of the tower.

Disadvantages:

- The higher the decant tower the more susceptible to failure from the movement of tailings.
- If a decant conduit should fail it is almost impossible to repair and can be very costly.
- Using a decant system can increase the pumping head if the pond is at a lower elevation to the mill.

3.3.5. Barge decanting

Barges don't interfere with the foundation or the structural integrity of the impoundment. The barge simply floats on the free ponded water controlling the water level by variable pumps generally housed on the barge. A pipeline from the barge to the embankment crest or out of the impoundment is supported by pontoons to prevent the pipeline being dragged on the tailings which can cause wear and possibly damage geomembrane and geotextile liners.

Advantages of a barge:

- One key advantage of a barge compared to the decant tower is that it can be relocated within the pond. This can be particularly useful when a single point discharge is moved which can alter the location of the free water over time. Also, if an impoundment has cells, the barge can be moved to active cells forgoing the need to install decant systems in each individual cell.

Disadvantages:

- If a power cut occurs the barge can no longer control the water level in the impoundment. Although if the power cut effects the processing plant (no tailings pumped to the impoundment) storm conditions can still raise the ponded water. With a decant tower the water can still be controlled if the decanted water goes to a pond outside of the impoundment, rather than be pumped direct to the mill which is susceptible to power failure. This would fill the conduit and tower full of water rendering it useless until power is restored.
- The barge and pump(s) require maintenance especially during below freezing conditions.
- During storm conditions the barge can only pump at a constant rate which is limited by the pump(s).

- A pump operator or controller maybe required to monitor the operations. This increases the costs.
- Once operations of the impoundment have ceased the barge will either have to continue pumping or drainage and runoff ditches will have to be installed to control the pond level.
- If the barge were too close to an embankment and tailings were picked up by the pumps there could be a potential failure of the embankment due to piping.
- Additional pipeline requires installing as the barge moves around the impoundment or cell as required.

Figure 33: Decant barges and pump house.

Figure 34: Pipeline pontoon supports.

3.3.6. Surcharge (Siphoning)

Siphoning is similar to having an overflow pipeline that decants the pond to maintain the maximum level of water possible. Generally a siphoning system is used on a decant or seepage pond located outside of the main impoundment as the volume of water is much less. If a siphoning system is used on the main impoundment it is to backup a decant tower or decant barge. Under no circumstances should an overflow pipe control the ponded water in an impoundment.

Two advantages are that they are cheap to install and can pass water in shallow conditions, but there are many disadvantages. The pipe is subject to cracking under embankment loading, particularly if the embankment is constantly raised. The pipes can easily get blocked by debris and can freeze easily rendering them useless.

3.4 Dewatering by non-mechanical means

Dewatering as a term that implicates the tailings relationships of solid and liquid phases, which can possibly be affected by the use of chemical means, is not an applicable method as an *in situ* treatment of the body of an operating tailings pond. This refers mostly to the water removal processes from the tailings that are used prior to the disposal of the tailings into the impoundment, and is generally included in the tailings disposal methods design. Most common practice of this kind of dewatering uses solid-liquid separation units such as thickeners, sometimes hydrocyclones and less commonly drum, disc and belt filters along with the use of chemical additives such as flocculants that mainly serve for sedimentation of the solids within the units used.

The main on land tailings deposition methods are wet deposition, semi-dry subaerial deposition, and thickened deposition. Differences of these deposition methods lay mainly on the water content of the tailings to be deposited, the point of discharge and the dewatering process of the tailings within the pond.

At the heart of the dewatering process are particle interactions with water. Vick [121] suggests that the dewatering ability of tailings will depend on the following factors:

a) particle size distribution (average D_{50} particle size)
b) the presence of very fine tailings (minus 2 μm)
c) the presence of clay and its nature

and as noted dewatering ability increases with increase in average particle size, decrease in percentage of fine material and lower clay content.

Effective dewatering requires attraction between particles as well as the maximization of particle contacts. As a process it can be divided into two stages having as a primary stage the addition of an additive (flocculant) that forms particle sedimenting flocs, and as a secondary the dewatering that follows. Conventional methods of tailings dewatering as presented above involve stages such as the use of pH control, the addition of flocculants/coagulants and surfactants to promote the formation of floc structures and amplify the settling rate of suspended solids during thickening. Rarely though they increase the tailings solids loading above 65-75% reflecting a pause of knowledge for further modification of the process and making the continual disposal of large volumes of tailings in dams.

Regarding the flocculants used in the dewatering process they are distinguished in inorganic and organic flocculants. Inorganic flocculants are mostly aluminium or iron salts that form insoluble hydroxide precipitates in water. Organic flocculants are natural or synthetic water-soluble polymers and are also called sedimentation, filtration etc aids depending on their final use. They are further classified into nonionic and ionic polymers (polyelectrolytes) and the ionic further subdivided to anionic, cationic and amphoteric types. Examples of inorganic and organic flocculants used are presented in Table 3 [116].

Dewatering of tailings requires extensive application of organic flocculants and especially flocculant types of a-PAA, c-PAA, PEI, PEO, PAS. It is not though always easy to predict which flocculant is most suitable to obtain the desired sedimentation rate. In general, anionic and nonionic flocculants are best for neutral suspensions that consist primarily of inorganic solids, whereas cationic flocculants are best for neutral suspensions containing predominantly organic solids.

An important factor that influence the choice of the flocculant seems to be the pH value since it determines the degree of dissociation of anionic and cationic polyelectrolytes. In general nonionics are well suited to acidic suspensions, anionic flocculants work well in neutral or alkaline environments and cationics are most effective on organic material and colloidal matter. Moreover a significant parameter is the flocculant addition since it appears to make a great difference to the process of dewatering. At a constant flocculant addition rate the suspension settles more slowly if the solids increases or if its average particle diameter decreases. Solids in a colloidal form may require an initial treatment with a chemical having strong ionic properties such as lime, alum or ferric sulfate (inorganic flocculants). They generally precipitate at neutral pH and produce a gelatinous, flocculent structure, which further helps collect extremely small particles [87].

Table 3: Inorganic and organic flocculants [116].

	Formula	**Comments**
Inorganic	Alum $Al_2(SO_4)_3 \cdot 14H_2O$	Used as powder (17% Al_2O_3) or 50% solution
	Aluminum chloride $Al(OH)_{1.5}(SO_4)_{0.125}Cl_{1.25}$	Used as solution 10% Al_2O_3
	Sodium aluminate $NaAlO_2$	Used as powder and solution
	Iron(III) chloride $FeCl_3$	Used as powder (100% $FeCl_3$) or 35-45% solution
	Iron(III) sulfate $Fe_2(SO_4)_3$	Used as a granulate
	Iron(III) sulfate chloride $FeClSO_4$	Used as solution 30-40%
	Iron(II) sulfate $FeSO_4.7H_2O$	Used as a crystalline powder
	Sodium silicate (activated silica) Na_2SiO_3	Used as a solution
Organic	Polyacrylamide	Main non-ionic organic flocculant
	Poly(ethylene oxide) (PEO)	Non-ionic, can be used like polyacrylamide with other flocculants
	Poly(sodium acrylate) (PAS)	Important anionic polyectrolyte, used mostly as a copolymer with acrylamide (a-PAA)
	Poly[2-(N,N,N-trimethylamino)-ethyl acrylate] (chloride salt)	Important cationic polyectrolyte, used mostly as a copolymer with acrylamide
	Polyethylenimine (PEI)	Cationic polyectrolyte with a high charge density in its neutralized form
	Poly[N-(dimethylamino-methyl)acrylamide]	Cationic polyelectrolyte formed from polyacrylamide, formaldehyde, and a secondary amine, mostly neutralized or quaternised (c-PAA)

Besides the conventional flocculant mediated gravity driven sedimentation in thickeners, it worth mentioning other methods that have been studied for dewatering of the tailings, although they were also implemented prior to placement of the tailings into the dam and using mechanical means. These include vibration, electrical methods, and use of additives.

Ritcey [93] has gathered information on these dewatering studies presenting the following: Vibration comprises a method of disturbance along with the use of bulldozers. It is implemented by dropping a large weight from a crane through a grid pattern achieving maximum settlement. The use of bulldozers across the bed maximizes compaction and reduces moisture.

Electrical methods such as electroosmosis and electrophoresis have been studied for dewatering tailings presenting high solid volume fraction and the application of filtration processes is uneconomical. In these techniques electric field is applied to move water out of a concentrated pulp (electroosmosis) or to move charged particles towards an electrode (electrophoresis). Although they provide a high dewatering rate it is not an economical treatment in the case of large volumes of tailings.

Furthermore the use of sand tailings as additives to slime tailings was reported to enhance the settlement rate of the tailings allowing retained water to be liberated.

3.5 Neutralisation of acidity

Addition of alkaline materials aiming at the control of pH is a commonly applied technique to prevent acid generation from sulphidic wastes. Materials like *lime*, [87, 48], *limestone* [26, 68], *sodium carbonate* [48] have been reported to effectively prevent acidic drainage. Industrial by products including *phosphatic slimes* and alkaline *fly ash* were also seen to inhibit acid generation. Studies on the effectiveness of limestone and lignite fly ash in inhibiting acid generation from highly sulphidic tailings were performed by NTUA within the EU research projects PIRAMID and ROLCOSMOS. Given that fly ash also possesses pozzolanic properties its potential use for the physical and geochemical stabilisation of tailings is discussed in the respective section.

3.5.1. Limestone / lime

The potential of limestone to prevent acid generation has been well recognised from the fact that in sulphide and coal mines containing abundant natural limestone or other carbonate minerals, limited if any acidity is formed. In sulphidic tailings when calcite is present, the overall oxidation-neutralisation reaction depends on pH [76]:

pH < 6.4

$$FeS_2(s) + 2CaCO_3(s) + 3.75O_2(g) + 1.5H_2O \rightarrow Fe(OH)_3(s) + 2SO_4^{2-} + 2Ca^{2+} + 2CO_2(g) \quad (1)$$

pH > 6.4

$$FeS_2(s) + 4CaCO_3(s) + 3.75O_2(g) + 3.5H_2O \rightarrow Fe(OH)_3(s) + 2SO_4^{2-} + 4Ca^{2+} + 4HCO_3^- \quad (2)$$

Based on the stoichiometry of reaction (1), under acidic conditions, 1 mole of pyrite is neutralised by 2 moles of calcite. At pH values above 6.4, the carbonate product will be HCO_3^- rather than CO_2. In this case, twice as much $CaCO_3$ is required to neutralise the same amount of acidity.

However, the addition and homogenous mixing of limestone with sulphidic tailings does not only neutralise the generated acidity but also can prevent the pyrite oxidation process by the activation of the appropriate physical and chemical mechanisms. In this case the cost of the method will be significantly reduced because the amount of additive required would be significantly less than the stoichiometric one (reaction 1).

There are four mechanisms by which limestone may control pyrite oxidation [78]. The first mechanism involves precipitation of ferric iron in the hydroxide form, thus its further participation as an oxidising agent in the dissolution of pyrites is inhibited. The second mechanism involves the raising of the pH of pore water to high values (pH: 6.1-8.4), thus the activity of the oxidising bacteria *Thiobacillus ferrooxidans*, is significantly impaired. Another mechanism involves the precipitation of oxidised compounds on the sulphides surface. It is reported that when carbonate minerals are present and available to neutralise the acid produced during the oxidation of pyrite, a protective ferric oxy-hydroxide layer will accumulate around the pyrite grains, impairing its further dissolution. Finally, according to field studies the presence of carbonate material in sulphide tailings may enhance the formation of cemented layers (hardpan) on the stockpile surface. The hardpan consists of the oxidation-neutralisation products such as ferric oxy-hydroxide and gypsum that cement the tailings together forming a low permeability mass that acts as an oxygen and water diffusion barrier.

“Quick lime”, CaO and “hydrated lime”, $Ca(OH)_2$ which compose *lime-kiln flue dust* exhibit twice the neutralisation potential of calcite, as shown in the following reaction [22]:

$$FeS_2 + 3.75O_2 + 2Ca(OH)_2 \rightarrow Fe(OH)_3 + 2SO_4^{2-} + 2Ca^{2+} + 0.5H_2O \quad (3)$$

Using a pure lime layer cannot be considered safe or practical and even when admixed with tailings may be detrimental as it readily dissolves and can be easily flushed away and would give rise to high pH seepage. Use of such material, as with Rotary Kiln Fines (RKF), would only provide short term mitigation.

3.5.2. BAUXSOL

Marketable reagents [122] have also been produced which are applied in a single stage in situ treatment capable of cleaning large volumes of tailings dam water and converting toxic dams into reservoir of clean water meeting stringent environmental standards. They are applicable for the treatment of heavy metals and acidity problems associated with tailings dams. These reagents are designed to treat either alkaline, mildly acidic, acidic, very acidic waters contaminated with heavy metals or sulphidic wastes. Products like Bauxsol, are materials that prepared by chemical and physical modification of the caustic red mud residue generated by the Bayer process, which extracts alumina from bauxite prior to electrolytic reduction. The material consists of sodium hydroxide which gives the material high alkalinity and also contains a complex mixture of iron and aluminium oxyhydroxides and alumino-hydroxy-carbonates. The mixture consists mainly of fine particles that have a very high surface-area-to-volume ratio and a high charge-to-mass ratio. The high pH of the alumina process waste enables heavy metals to form their least soluble and least mobile compounds (see http://www.waterforlifelimited.com). The exact composition depend on the composition of the bauxite used at each refinery, while different blends are prepared by adding small quantities of natural minerals or other chemical substances to improve its performance for each case applied. They mainly used as a mixture of slurry using water from the tailings dam, which is then sprayed onto the surface of the dam. The good dispersion properties of this reagent ensured that there is an even coverage for the entire dam. This results in the production of extremely thin and dense sediment on the floor of the dam, which acts a passive barrier for treatment of ingress of acid mine drainage.

The process has been successfully used at the Mount Carrington tailings dam in New South Wales. The treatment of the dam involved adding several varieties of Bauxsol to water pumped from the dam in a high volume-recirculating mixer and then dispersing the resulting suspension over the dam's surface. As the Bauxsol settles out of the water, it neutralised the dam water, raising the pH from 5.2 to 7.3. At the same time, the Bauxsol reacts with dissolved heavy metals and reduces the dissolved aluminium content from 1060 to 13 µg/l, dissolved cadmium from 310 to <1 µg/l, dissolved copper from 1510 to 3 µg/l, lead from 16 to <5 µg/l and zinc from 11570 to 49 µg/l. As a result of the process, the impounded water meets with drinking water guidelines and, after passing through a large sand filter, can be released into local streams.

When the dam is emptied, the reacted alumina waste will form a blanket of inert sediment in which the dissolved heavy metals are trapped. The blanket also isolates tailings and prevents contaminated pore water from interfering with the treatment of the surface water.

3.5.3. Hardpan formation

Decomposition of iron sulphides in an alkaline matrix and subsequent precipitation of secondary oxidation-neutralisation products can lead to the formation of a hardpan layer. The natural formation of a hardpan layer at the tailings surface has been reported in a number of studies and given the significant environmental and economic implications of this layer. The main conclusions regarding hardpan formation include:

- Hardpans are formed at the tailings disposal areas tens of years after the end of deposition.
- Hardpans are observed at a depth of few centimetres from the tailings surface, in the interface of oxidation zone with the underlying non-oxidised tailings and have a thickness ranging from 1 to 15 cm.
- The formation of a hardpan layer is enhanced under strong oxidative/alkaline conditions, resulting from the occurrence of highly reactive sulphides, i.e. pyrrhotite and alkaline minerals, i.e. calcite. In all the study cases, tailings exhibited a negative net neutralization potential.
- Hardpans formed by sulphate minerals, e.g. gypsum, are more persistent laterally as compared to those consisting of ferric hydroxides, which occur as discontinuous mineral segregations with a limited lateral extension.
- Hardpans are characterized by low hydraulic conductivity, i.e. $k = 10^{-8}$ to 10^{-9} m/s, and greatly reduce the diffusion of oxygen into the underlying tailings, inhibiting the oxidation of contained sulphides. Adsorption of dissolved metals like Zn, Cd, As, Mn, Ni, Co to the precipitated compounds in the hardpan layer limits their downward migration and subsequent groundwater contamination.

3.6 Improvement of geotechnical properties of tailings

3.6.1. Cement

The addition of a cement additive to tailings is often practiced in underground mine backfill applications, owing to the resulting material having high compressive strengths. This cement addition procedure has potential benefits for use during the decommissioning of tailings dams as this can give chemical and mechanical stability to the material and can also be used as a

cover material. For individual operations investigations need to be carried out to identify suitable materials to act as a binder/cement. The basic properties of cement slurries and pastes used in the mine backfilling have been extensively studied, and it is felt that a lot of this knowledge can be applied to systems used for the decommissioning of tailings sites. Some studies on tailings treatment with cement are briefly reviewed below.

Laboratory tests using tailings of fine grained pyrite and other metal sulphides showed that the addition of high alumina cement produced a backfill with suitable strength and permeability. Mixes with cement contents of 7.5-15% (by weight) and w/c ratios of 1-2 showed strength values up to 25 MPa after 128 days curing and very low permeability values. No AMD was produced from the mixes. The elution behaviour was sufficient with regard to requirements for waste disposal sites. The consistency of the mixes made them suitable for hydraulic transport with concrete pumps.

Jones and Wong [59] examined the use of cementitious dry surface covers for the prevention of water and oxygen infiltration into acid-generating wastes. The field trial covered 3500 m² and the objective of the study was to evaluate the material properties and long-term efficacy of the 8 cm thick cementitious cover. The test site was resloped at 22˚ and compacted prior to the shotcrete being applied. The capping system was designed to connect with a diversion ditch system. The compressive strength of the cemented cover material increased with time (20-35 MPa). From this work it was shown that it may be necessary to landscape and engineer the reactive tailings material prior to the application of a cover. This would allow rapid drainage and minimise any standing water which could soak into the tailings.

Verburg et al. [119] added 5% by mass of Ordinary Portland Cement (OPC) to enhance the geotechnical properties of the tailings, being ultrafine pressure leach residues approximately 55% -20 µm in size. Average strengths of 2.1 Mpa (300psi) were achieved after 28 days of curing.

One of the negative aspects of cement covers is that the covers can crack and allow water and air access and lead to further degradation. When the cover is placed on unconsolidated tailings material, the barrier may mechanically breakdown as the tailings dry or subside. Long-term predictions on the behaviour of these covers are very difficult to assess and at best can only be estimates. Any cracks that may appear will need to be cemented and sealed to minimise further degradation. Long-term maintenance would therefore still always be required.

Cost is obviously an important consideration and the availability of various types of cheap additives needs to be carefully examined. The tried and tested addition of OPC is considered to be too costly for a large volume tailings cover. However, other cheaper alternatives including *Blast Furnace Slag (BFS), Pulverised Fly ash (PFA)* and lime can be locally available and can

be easily substituted in the cement mixtures. The substitutes used need to be critically evaluated to ascertain the optimum cement mixture to achieve suitable mechanical properties.

3.6.2. Fly ash

Fly ash is the material trapped by electrostatic precipitators in coal and lignite burning power-generating plants. The quantity of fly ash annually produced in the world is estimated to 200 million tones, of which a percentage of 20% is used in various applications including cement and concrete industry, flowable and structural fills, road base, waste stabilisation and solidification, mining applications, agriculture dressings, land and eutrophic reclamation.

Fly ash is composed of predominantly silt-sized, spherical, amorphous ferro-aluminosilicate minerals and it is generally characterised as a low permeability material [102]. The physical, chemical and mineralogical characteristics of fly ash depend on the parent coal source, the method of combustion and the efficiency and type of emission control device. Two major classes of fly ash are specified in ASTM C618 on the basis of their chemical composition resulting from the type of coal burned. They are designated as Class F and Class C. Class F is fly ash normally produced from the burning of anthracite or bituminous coal ($[SiO_2+Al_2O_3+Fe_2O_3] \geq 70\%$). Class C is normally produced from the burning of subbituminous coal and lignite ($[SiO_2+Al_2O_3+Fe_2O_3] \geq 50\%$). Class C fly ash has cementitious properties in addition to pozzolanic properties due to free lime, whereas Class F is rarely cementitious when mixed with water alone.

Class C fly ash due to its increased Ca content (in the forms of CaO, $Ca(OH)_2$, $CaCO_3$) has significant neutralisation potential and may be beneficially employed to counteract the acid potential of the mine wastes [29, 98, 106, 107]. The neutralisation reactions of three high-Ca fly ashes (Ca 15-22% wt.) with HCl were studied by Hodgson et al. [50]. Three distinct buffer zones were determined: a high pH region (pH 12.0-10.5) accompanied by dissolution of Ca, a second region (pH 9.2-8.5) with the concomitant dissolution of Mg and a third region (below pH 4.2), in which Al was released from the fly ash matrix.

Fly ash has been added as an alkaline amendment to coal mine spoils and refuse banks to permit their reclamation for plant growth [8]. Amendment of acid soils with up to 1% wt. fly ash, containing 30-40% Ca, increased pH and reduced the solubility and DTPA extractability of Fe, Mn, Ni, Co and Pb [89]. It was demonstrated that the alkalinity of fly ash plays a significant role in regulating the availability of trace elements in the amended soils.

At the Gilt Head mine, reactive tailings were mixed with locally available PFA which provided sufficient neutralisation potential. The addition of water allowed solidification of the PFA to take

place. The tailings were added to PFA at a rate sufficient that the acid neutralisation potential to acid generation potential (ANP:AGP) ratio is greater or equal to 3. The PFA used exhibited an average neutralisation potential of 467 kg/t and was added at a rate of 25 t/10,000 t of tailings. The tailings were finally capped with a low permeability clay liner (~30 cm) (http://www.state.sd.us/denr/documents/epasspap.pdf).

Given the pozzolanic and cementitious (for Class C) properties of fly ash, this material may be beneficially used to modify the physical properties of the wastes by decreasing their permeability to water and air, thus hindering oxidation of the contained reactive minerals. Bowders et al. [13] have concluded that fly ash amended with clay and sand would be beneficially used in the construction of a surface hydraulic barrier to control acid generation from surface mined sites. Taha and Pradeep [111] evaluated the potential use of fly ash-stabilised sand mixtures as cover materials for sanitary landfills. It was seen that sand mixtures stabilised with 20% fly ash had a low permeability in the order of 10^{-8} m/sec, increased unconfined compressive strength and increased resistance to freeze-thaw and wet dry cycles.

PFA has been used in a number of pilot projects to reduce rainfall infiltration in areas that are subject to acid mine drainage [104]. In research conducted at a site in Pennsylvania [104] this was capped with 520,000 tons of PFA grout, which exhibited low permeability characteristics. This grout was determined to have a permeability of 10^{-9} m/sec which is equivalent to that of bentonite clay. A 1 m layer of PFA grout was placed in 15 cm compacted lifts after the surface was prepared by removing 1 m of surface soil and compacting the exposed surface. Upon completion of the PFA placement the soil was replaced and grass planted. AMD was monitored and was shown to have been effectively reduced.

Other potential benefits of utilising fly ash in reclamation include providing fines for seeded improvement and to increase plant available moisture retention, improving the soil bulk density and providing plant micronutrients. Class F fly ash was successfully used as a soil amendment to prepare anthracite refuses for direct revegetation [18]. Fly ash amendment improved the physical and chemical characteristics of the anthracite refuse by increasing the plant water-holding capacity, shifting the textural class of the refuse from sandy loam to silt loam and improving the pH and fertility of the coal refuse materials.

The main drawback for the extensive application of fly ash as an alkaline amendment is associated with the contaminants often contained in fly ash and the adverse impact that their release would pose on the environment. Depending on the coal source, fly ash varies widely in the pH of its generated leachate and trace element content, which generally exceeds those typically present in soils. Various studies of fly ash leaching behaviour have shown that pH is the principal control on trace element leachability. The rate and amount of the minor elements

released to solution during the leaching of fly ashes are also influenced by their total concentration in the ash, their distribution among the solid phases of the ash and their incorporation into secondary solids as a result of precipitation reactions following the addition of water. Previous studies, Duchesne and Reardon [32], have shown that the trace elements leached in appreciable amounts are those that form anionic species like $H_2BO_3^-$, CrO_4^{2-}, MoO_4^{2-} and AsO_4^{3-} in alkaline environments. The accumulation of B, Mo, Se and soluble salts appear to be the most serious constraints associated with land application of fly ash to soil [106]. High boron and soluble salts concentrations in the soil can be toxic to growing plants whereas high Mo and Se uptake by plants are potentially hazardous to foraging animals.

The effect of various lime treatments on the solid phases and the leachate compositions for a Class C and a Class F fly ash was investigated by Duchesne and Reardon [32]. The treatments reduced the leachability of B, Cr, Mo and SO_4 contained in the fly ash. Treatment of class F fly ash with lime resulted in the formation of hydrocalumite ($Ca_4Al_2(X)^*(OH)_{12}\cdot nH_2O$), an anionic clay which can accommodate anions like borate, chromate and molybdate into its interlayer region. With Class C fly ash, the lime treatment generated hydrogarnet ($Ca_3[Al(OH)_6]_2$), which has less sites for anion substitution and ettringite ($3CaO\cdot Al_2O_3\cdot 3CaSO_4\cdot 32H_2O$). Ettringite can accommodate ion substitution in several lattice sites: CrO_4^{2-} and MoO_4^{2-} can replace SO_4^{2-}; Sr^{2+} and Ba^{2+} can substitute for Ca^{2+}; and Fe^{3+}, Mn^{3+}, Cr^{3+}, or Ti^{3+} can replace Al^{3+}.

3.6.3. Bentonite

Bentonite is commercial clay of the smectite group consisting primarily of montmorillonite has a wide application in the tailings management facilities either as liner, covers or cut off wall. It's mixing with sulphidic tailings at a proportion of 5-18% w/w, has resulted to the reduction of the overall hydraulic conductivity and permeability while also to the reduced metals leachability [79]. Properties of bentonite and especially of sodium bentonite include high swelling capacity, thixotropic behaviour, good plasticity, high shear strength, low permeability, compressibility and consolidation values, properties that are considered desirable for the body of a tailings dam, make it a valuable material for the improvement of the geotechnical characteristics of the tailings.

3.6.4. Combinations

Tailings from the Mineral Hill gold mine in Montana consist of finely ground siliceous rock processed by cyanide leaching. They were mixed with a cementitious paste consisting of PFA, OPC and water with a water/cementitious materials ratio of 0.83 and a high paste volume (52

vol%). Cement content was kept low (8 wt%) by using a high volume of PFA in the paste. The resulting material experienced noticeable shrinkage, but no cracking, as it cured and dried. Cylindrical specimens tested in unconfined compression had strengths as high as 23 MPa. Standard shaped masonry units were cast from the tailings concrete and had strengths which exceeded requirements [27].

The effectiveness of cementitious compounds such as cement, fly ash and polymer and organic based solutions in retarding or preventing the production of acid mine drainage from mine waste rock and reactive tailings was evaluated by Farah et al. [37]. The control waste rock sample produced acidic leachates with pH of 2.5 after a 22-week period. The treatment of waste rock with cementitious compounds resulted in the production of leachates with pH value of 12. At the end of the test period the pH dropped to about 8. Under these alkaline conditions, Fe and Ni concentrations in the solution were insignificant. It was concluded, however, that the polymer and organic based solutions were more effective in retarding acid generation than the cementitious materials.

Reactive pyrrhotite tailings can be agglomerated using the cold bond tailings agglomeration process with Portland cement and PFA as low cost binders. Various chemical additives were used to retard acid mine drainage including acid neutralisers, surfactants, sealants and bactericides, which were encapsulated into the agglomerates. A study was made of the long-term stability of these reactive tailings agglomerates, with respect to acid mine drainage, when disposed of in underground paste backfill. Kinetic stability tests were carried out and pH, redox potential, conductivity, sulphate, acidity and dissolved metals were monitored. Results showed that most of the encapsulated additives retarded acid mine drainage [1].

Benzaazoua et al. [5] studied the physical/mechanical and geochemical characteristics of cementitious mine backfill with high sulphur content. The backfill consisted of tailings averaging 10% wt. S content. The binder was a mix of fly ash (40%) and ordinary Portland Cement, OPC (60%) and represented 94.5% of the backfill total dry weight. Analysis of core samples showed the presence of a fine system of fractures accompanied by oxidation traces. Oxidation of sulphides in the tailings caused the dissolution of the alkaline hydrated phases of the binder including portlandite, hydrated calcium silicates and sulfoaluminate and the precipitation of iron and aluminum hydroxides and gypsum. Chemical alterations resulted in the degradation of the backfill's mechanical properties.

3.7 Passivation of sulphidic minerals

3.7.1. Phosphates

The use of phosphate rock and related materials can be used on account of their neutralisation potential [124]. Neutralisation reaction's will produce secondary minerals such as gypsum and ferrous phosphate and these compounds may block pore spaces and reduce tailings permeability with time. The patented EcoBond process can be applied in wet or dry form, applied in-situ or ex-situ, stabilize metals within 24 to 48 hours of application, and increase the volume of the waste by only 1% to 5%.

3.7.2. Sodium Silicate

Coating of the sulphide minerals with silicates is possible by treating with a solution containing H_2O_2, sodium silicate and a buffering agent. The H_2O_2 oxidises a small part of the pyrite and produces Fe(III) ions. These ions subsequently react with the silicate ions to produce ferric hydroxide-silica that precipitates on the pyrite surface producing a passive coating [43].

In a study by Bowel [14] it was identified that for highly reactive tailings, i.e. pyrite-rich tailings silica encapsulation appears to be the most efficient method for reducing AMD. While this may be the most expensive treatment option it can be highly efficient. This method could possibly be employed as a layer and used in conjunction with a sized product to minimise the addition of sodium silicate. While the silicate process is highly effective, the high cost considerations may outweigh the use of this material. Other fixation methods using sodium silicate and Portland cement have also been suggested, but these are more practical for small volume chemical fixation.

Factors governing the formation of geopolymers are still poorly understood, although their physical and chemical properties suggest that their matrices are more suited for the immobilization of toxic metals. Research has indicated that the long-term durability of ancient mortars results from their high levels of zeolitic and amorphous compounds. Geopolymers can best be viewed as the amorphous equivalent of certain synthetic zeolites. Their structures are described as poly(sialate) with -Si-O-Al-O- as repeating unit, poly(sialate-siloxo) with -Si-O-Al-O-Si-O- repeated and poly(sialate-disiloxo) with -Si-O-Al-O-Si-O-Si-O- repeated; they are also referred to as alkali-activated alumino-silicate binders. As cementitious products with high early strength, fast setting, low permeability, acid resistance and low cost they have numerous possible applications [118]. Sealants studied included those with cementitious compounds and aqueous sealants such as polyurethane and natural resin-based solutions. Representative mine waste rock was prepared using various surface coatings and allowed to weather naturally over

seven months. Leaching tests were also set up in the laboratory to monitor the oxidation process of typical mining waste materials to provide control of various factors such as air, temperature and moisture. Viscous liquid barriers use permeation grouting to place inert liquids that increase in viscosity over time. Using injection from multiple points, an impermeable wall can be constructed without disturbing the soil matrix or damaging structural features like tanks, pipes, and cables. Materials such as colloidal silica and polysiloxane are mixed with a brine solution to control the material set time following emplacement [118].

UNR process

The UNR process involves the deposition of a stable coating on the surface of the individual pyrite grains thus preventing their oxidation. This method is a modification of the DuPont Process which uses potassium permanganate and an inexpensive coating agent, such as magnesium oxide, which can be applied at a lower pH range (9-10). The passivation results using this method on pure pyrite, waste rock and mine tailings show some success but has not been proven on a large scale [70].

3.7.3. Inhibition of bacteria action

Certain bacteria are known to increase rapidly the rate of acid production from pyritic materials. Bactericides have been developed which inhibit the growth of these microorganisms. Their primary effect is minimising the catalytic role played by bacteria in converting ferrous iron to ferric iron under acid conditions. It has been noted that theoretically these bacteria can accelerate the rate of reactions in the complex series of the interrelated reactions of AMD by a factor of 10^6, a fact that in real conditions has been observed to reach acceleration factors up to only 5. Therefore the use of bactericides can be an intervention action in the case of sulphidic tailings body that pose a threat through acid generation reactions. Bactericides aim to create a toxic environment for bacteria so that bacterial oxidation will be inhibited without chemical oxidation will be reduced at a high rate. Their advantages lay on the non-resulting sludge that is mainly produced with the use of lime and that trace metals are very tightly bound within this sediment without any risk for their release in the case of new inflow acid water.

Many chemicals including antibiotics, anionic detergents and food preservatives have been used as bactericides [93]. Antibiotics present a very high cost. Most popular anionic detergents that have been used successfully as bactericides include sodium lauryl sulphate (SLS) and sodium/potassium benzoate. Both antibiotics and anionic detergents can pose a threat to

aquatic life in certain concentrations. The use of food preservatives such as benzoate and sorbate salts is not toxic to aquatic life but the cost for their applicant is prohibited.

The usual technique employs the dissolution, generally in a powder form bactericides in water and spraying the resulting solution over the tailings. Moreover their application can take place by admixing them with the tailings prior to disposal. This can constitute though to their degradation by micro-organisms and can be flushed with water. Therefore their successful implementation requires that spraying will occur periodically, every 3-6 months. This disadvantage has been studied and slow-release pellets that have been produced containing surfactant impregnated rubber are suggested, reporting to remain active for 2 years.

3.7.4. Amelioration of the tailings to support vegetation

During this phase of the tailings dam operation, different practices could be introduced in order to ameliorate the tailings characteristics to support vegetation after closure. Revegetation continues to be the prime option for reclamation of tailings impoundments since in this way complete long term rehabilitation can be achieved. It should be mentioned that revegetation has been planned for many currently active impoundments, relatively only a minor number of reclamation programs have been carried out to successful completion.

In order to achieve that, vegetation requirements should be studied in accordance to the tailings characteristics. Vegetation is dependent on two principal factors [121]: climatic characteristics and the nature of the growth medium. Soil characteristics that influence vegetation growth in general include:

a) Texture
b) Fertility
c) Toxicity

These are physical properties along with compaction, available water-holding capacity and permeability. Chemical properties can include mineralogy, acidity, alkalinity, salinity, cation and anion exchange capacity, organic matter and available nutrient content. Moreover biological factors can be considered such as microorganisms.

Morrey [77] summarized the main relative parameters (Table 4) of mine tailings that affect vegetation.

Table 4: Parameters affecting vegetation on mine tailings

Chemical	Physical	Biological
Low pH	Compaction and run-off	Sterility
Salinity	Low/excessive infiltration	Lack of nutrient cycling
Toxicity	High temperatures	
Nutrient deficiencies	Surface mobility	

Texture describes the content of sand, silt and clay sized grains in the soil. The texture of the soil dictates the porosity and permeability of the soil that determines the retention and penetration of moisture, nutrients and roots of plants. A soil predominant with sand has poor bonding and moreover it is susceptible to wind and water erosion without easily retaining moisture and nutrients. Silty soils may be finer grained, bond better and retain moisture and nutrients, they are susceptible though to wind erosion due to their finer grain size. The clayey soil is a good medium for vegetation and it is a very fine grained and easily compacted material presenting low porosity and low permeability. It has been reported [45] that the optimum mix for vegetation should be a soil with 20-30% clay, 30% sand and 40-50% silt.

Tailings from this standpoint of view are usually of a very fine structure having high water retention capacity, while their treatment to consolidate and compact on the surface or even be cemented, form an impenetrable surface barrier. Even if they do not follow such processes of compaction due to their fine grain size are susceptible to wind erosion, which inhibits plant growth. Tailings are also characterised by lack of essential nutrients required for plant growth, including nitrogen, potassium and phosphorus as well as bacteria and fungi.

Before considering the use of fertilizers, analysis of the soils as well as determination and possible correction of the pH due to acidity or alkalinity present must be completed first. It is important to know that there are a limited number of plants that will survive in a soil that has a pH too high or too low. For example above pH 8 phosphates can combine with calcium to form an insoluble compound unavailable to plants and below pH 5 aluminium and iron may also be combined with phosphate to the formation of an insoluble compound. When tailings of sulphidic content are present there is a necessity to raise the pH to above 4.5 and enable the selection of many more species for vegetation.

The most cost effective method for raising the pH is lime, as has been used and mentioned in the paragraph of tailings neutralization. Its application rate in order to treat acid soils with a pH of 4.0 or above uses the following ranges of lime addition: 2-5 t $CaCO_3$eq./hectare when pH

ranges from 6.0 - 5.5, 6 - 9 t $CaCO_3$eq./hectare when pH ranges from 5.4 - 4.6 and 10 - 13 t $CaCO_3$eq. / hectare when pH ranges from 4.5-4.0.

Fertilizers needs are given according to the three major nutrients which are nitrogen (N), phosphorus as an oxide (P_2O_5) and potassium as an oxide (K_2O) usually referred to as N P K. the amounts are expressed as a ratio according to weight, therefore 6% N, 6% P_2O_5 and 6% K_2O is expressed as 6:6:6. In this case of the tailings pond where it is still in operation the amelioration of the tailings in terms of fertilizers can occur by the use of organic fertilizers that have been proved to be most beneficial, which include sewage sludge, garden mulch, crop mulch, manure and wood chips. Especially in the case of freshly derived wood chips they should be allowed to be deteriorated before being used in order to avoid take up of nitrogen already present in the soil.

Toxicity of the growth medium will stunt or kill developing plants. While heavy metals such as iron, manganese, zinc and copper are necessary in very small quantities for healthy plant growth, their presence in higher concentrations may slow or preclude plant development. The use of lime though for neutralization of low-pH tailings has shown that also renders metals insoluble, reducing thus their availability to plants. At this stage thus periodic reapplication of lime may be helpful.

4 Strengthening of tailings impoundment by conventional engineering methods

4.1 General remarks

Engineering methods of strengthening are used to improve the stability and the deformation behaviour of tailings impoundments. In the different states of life cycles of tailings facilities like operation, closure, rehabilitation and area after use, we need a wide range of different conventional and unconventional methods, depending on the characteristics of each period. In principle two types of risks exist:

- environmental impacts through pollutants of deposits of an operational tailings impoundment without stability risks
- stability failure with respect to reuse of the area

In this chapter the necessary intervention actions to guarantee safety in the different states will be determined. In most cases the various engineering methods on the base of monitoring are able to protect the surrounding environment and human life. For rehabilitation the monitoring measures have to be continued or replaced by natural systems, so that a new acceptable level of release is archived (curve B - Figure 35). On this base further possible engineering intervention is declared. The release of pollutants is restricted. Otherwise if no attempts are made the release of hazardous substances can exceed defined limitations (curve A - Figure 35).

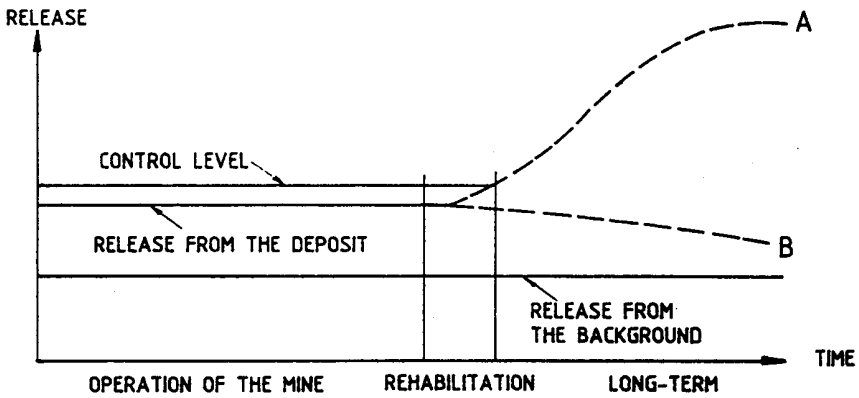


Figure 35: Release levels from a tailings dam with time [55].

4.1.1. Environmental Hazards

In the design and construction of tailings facilities the engineer is faced with two different kinds of hazards. These are the possible release of very large volumes of semi-fluid tailings due to loss of structural stability and the possibility of pollution of the ground and groundwater due to ingress of polluted liquid from stable dumps.

There is a difficulty associated with specifying reasonable short-, medium-, and long term stability requirements, especially if environmental considerations are taken into account. The environmental impacts influence the stability and the deformability of the tailings impoundment. Derived from these, the risk for life and further constructions in the surrounding area are to be estimated and considered in different terms. This is to ensure that no catastrophic embankment failure occurs during the operational life of the dam. An important element in the development of a strategy to provide a common approach to safe design, construction, operation and rehabilitation has been the development of the hazard rating systems. These are not only the basis for classifying and registering but also for defining the ongoing design and operational standards required to provide acceptable levels of safety, minimal environmental impact and adequate rehabilitation.

To prevent environmental impacts associated with embankment failure from occurring it is necessary to strengthen with conventional engineering methods, these are:

- Flooding caused by heavy rains and storm conditions
- Cyclical and dynamic events, for example earthquakes
- Frost

Flooding can be managed by increasing the freeboard of the impoundment during design and construction, and in the long term the use of monitoring systems by different intervention and strengthening methods. However, this results in additional water in the impoundment available for seepage. Using the freeboard may be economical in semi-arid areas where flooding occurs infrequently and the mine requires a large amount of water for processing streams.

Cyclical and dynamic events are in most cases earthquakes. Concerning embankment dams the average annual failure probability is mostly lower than 10^{-6}, but it may be in the range of 10^{-3} for some dams in seismic areas. Seismic behaviour of tailing dams includes settlement, horizontal movement, cracking (longitudinal and/or transverse), pore pressure increase, slope slumping, slope failure, liquefaction, internal erosion, seepage increase and impoundment breaching.

The effects of frost and ice on tailings and their containment structures can be large and have an influence on the long-term stability. Frost can cause problems for any structure built on

saturated soils. As the pore water spaces consist of ice, then once thawing occurs a release of a greater volume of water than can be normally accommodated by the soil pore space occurs. The once frozen water saturates the soil with excess water and the strength of the soil mass is reduced. Normally the effects can be divided into two groups, the ice accumulation and the seasonal frost action. In areas of severe winter where continuous or discontinuous permafrost develops, ice accumulation should be taken into consideration. During placement of tailings onto beaches, layers of frozen material may be formed. The thickness of each layer depends on the climate and the rate of use of the impoundment. The effect of freezing tailings is to prevent consolidation and drainage for as long as the tailings are frozen. In northern Canada large accumulations of frozen tailings have occurred under the beach areas of annually layered tailings impoundments. The zones under the pond tend not to freeze. Similar effects can occur in Eastern and Southern Europe, when tailings are deposited during strong winter temperatures. On thawing the low density frozen tailings will consolidate resulting in large surface settlements and pore water pressure. Such settlements would disrupt surface drainage and capping layers.

4.1.2. Impoundment reliability during operation term

Safe tailings storage depends on the type of tailings facility, the tailings lagoon and tailings pond which is to designed to protect against external erosion by water and wind, contamination of the foundation, the surrounding environment by high phreatic water level and internal erosion.

The reliability of water control facilities for inflow process water, natural tributary and precipitation supervision is of special interest. Seepage can be influenced by:

- ending of tailings deposition for a determined time interval to decrease water levels by removing decant and pond water
- changing of discharge location
- additional removing of water at single locations, i.e. vacuum wells in the tailings impoundment and rearranging of additional drainage systems on the embankment face and toe.

The external erosion protection for operational tailings facilities can be generally influenced by strengthening or covering with permeable material, or by irrigation during processing when the lagoon surface becomes dusty due to higher evaporation than precipitation.

Failure from internal erosion is more complicated and these processes are difficult to discover and to prevent. Rehabilitation procedures can be based on temporarily removing the seepage water for building in permeable materials affecting impoundment parts or partially clogging the existing drainage system. In cases, where additional operations on the impoundment are not

successful extending methods can be used. These can be rock facing, sheet piling and grouting. The technical equipment for controlling the water flow can also be defective. Methods like installation of redundant technical systems can improve the safety of the impoundment. Finally leakages near the tailings facility due to high phreatic water levels are removed when pollutants, which exceed the allowable concentrations can affect the environmental system. To reduce these risks, passive dewatering systems that catch the seepage water in special treatment installations can be operated as well as dewatering systems by additional arrangement of wells.

The various actions for intervention are explained in the following chapters.

4.1.3. Impoundment reliability during rehabilitation and after use

The principle difference in stability between the operation time and long term phase is in the phreatic conditions. Ordinarily when tailings discharge ceases and a continuous source of water no longer supplies the decant pond, the phreatic surface within the embankment drops dramatically, resulting in a greater slope stability after reclamation than during operation, on condition that natural tributary and precipitation will not fill up the pond.

For safety decisions the flow path of this additional water must be observed, so that the volume of water that infiltrate the embankment as pore and seepage water can be expressed in terms of a maximum possible level. The water percentage which doesn't infiltrate still remains as free water in the tailing pond or in special cases in the free water cover system. The technical devices for water level regulation are to control the rehabilitation time including those for long-term procedures. During the closure period as a transition to long term, the tailings impoundment should be controlled with different monitoring systems for measuring all significant quantities and concentrations. The measurements shall contain [3]:

- erosion behaviour on all free surfaces
- possible chemical solutions and their concentration
- impact on groundwater due to seepage water and the resulting contamination
- pollution formation and conditions along the downstream pathway
- dust emissions
- establishment of flora and fauna

Dependent on the results of the construction of the tailings impoundment, the water control systems, drainage system and possible cover system are to be accommodated, so that from the economical point of view no technical equipment is necessary. Various design methods to

achieve these objectives are available, which differ according to climate, site conditions, nature of the tailings, type of impoundment and regulation requirements.

The tailings impoundment will generally exist much longer than the mine or mineral processing plant has ceased to function. Therefore during the planning phase the long term safety is taken into account. These points may be considered for example [54]:

- The engineering aspects and long term surveillance of the scheme in order to address long term stability and safety
- Environmental controls to avoid groundwater contamination from seepage arising from stored residues, or air pollution from dust, or hazardous emissions and
- Some form of rehabilitation plan to take place on completion of the scheme or as a part of an ongoing restoration program.

In this context it is necessary to distinguish between tailings facilities with toxic, acid or similar dangerous substances for environment and human. Derived from these tasks the following key objectives for rehabilitation and closures are emphasised [54, 103]:

- Stabilisation of the impoundment (long term stability, seismology, erosion, protection, drainage system)
- Hydrology (long term assessment of catchment runoff and diversion arrangements, including risk of overtopping and breaching)
- Contamination (leachate control or containment, surface and seepage water quality, emission control and dust hazard)
- Visual impact (ground countering, planting and soiling, landscape measures)
- After use consideration (restoration for leisure, agriculture or commercial enterprise, return to the natural cycle)
- public accessibility and inherent dangers (long term surveillance and monitoring).

4.2 Methods of strengthening / stabilising

4.2.1. Rock facing / rock riprap

If the slope surface consists of rock or cobble fills, no special slope surface treatment is necessary. Downstream slopes with outer sand and gravel should be protected against erosion caused by wind and rainfall run-off by a layer of riprap, a kind of rock facing, or sod. Riprap is nothing other than a strong cover of the downstream slope.

Figure 36: Water erosion channels and erosion cracks in a tailings dam.

Rock facing, rock riprap or buttresses stabilise existing slumps and prevent potential slumps. Furthermore ripraps can be used because of their porosity as a drainage layer. In composition with an underlying permeable layer or geotextile the leachate of the phreatic line in a downstream slope can be avoided. The arrangement of riprap on an impermeable liner (Figure 37) in context with leachate of seepage water can increase the phreatic level inside the dam during construction. It follows that the motivating forces on the base of pore water pressure can increase the risk of failure of the embankment.

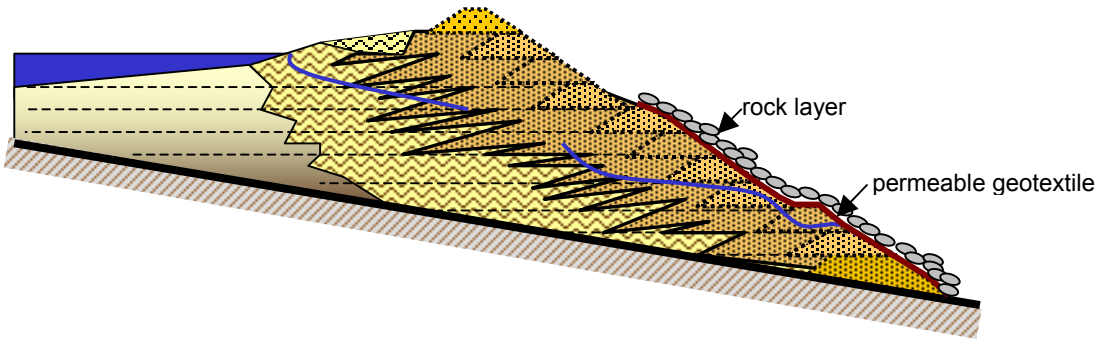


Figure 37: Rock riprap protecting the downstream surface of tailings embankment in composition with an underlying permeable layer.

Because of the uncertainty of obtaining adequate protection via a vegetation cover in dry Southern European regions, protection by cobbles or rock should be used. A 30 cm thick layer usually affords sufficient protection. The rock riprap should be installed in such a manner, that displacements can be avoided. A modified method of rockfacing is the arrangement of gravity layers on the toe of embankments (Figure 38).

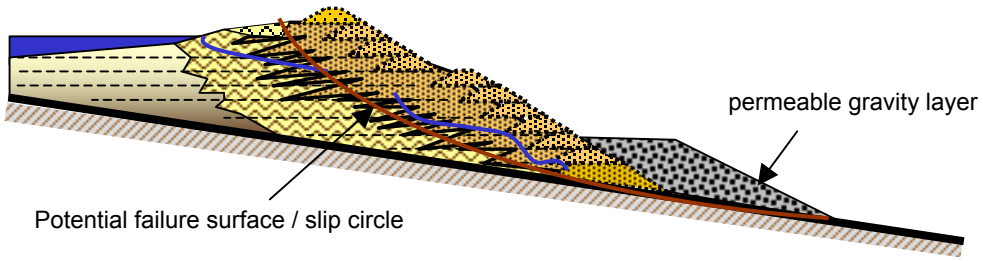


Figure 38: Upstream tailings dam enlarged by toe loading.

The toe-loading shifts the centre of gravity downwards and decreases the potential of slumping. Both methods can be used against underground suffusion or internal suffusion. The gravity mass in combination with the grain size distribution of installed permeable rockfacing can act as a filter. The progress of suffusion can be stopped.

4.2.2. Sheet piling

Sheet piling (Figure 39) may be composed of steel, timber or concrete piles, with each pile being linked to the next to form a continuous wall. Sheet pile walls are sufficiently watertight for most practical purposes.

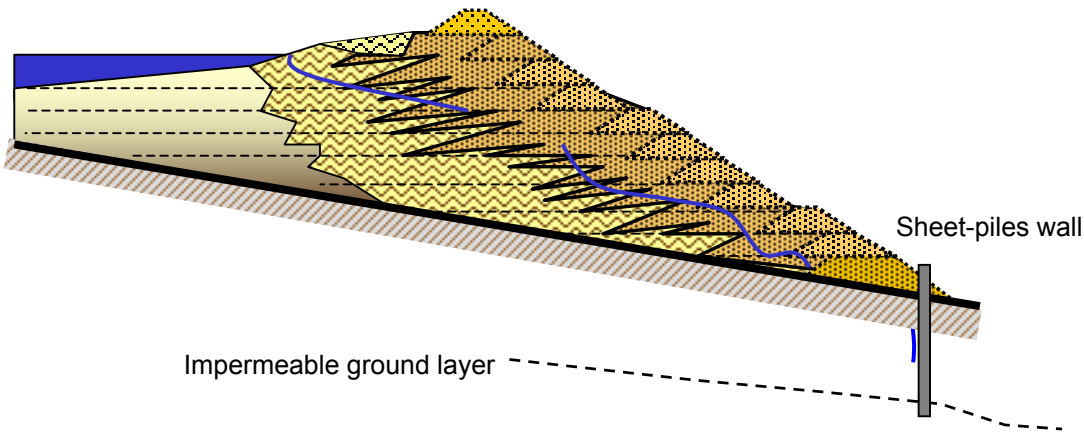


Figure 39: Upstream tailings dam with sheet-piles wall.

Sheet piling methods are used to form barriers against groundwater flow and in this manner as a barrier against downstream groundwater pollution. Steel sheet or concrete piles are generally used for forming water barriers and supporting the ground at the same time as construction or remediation of embankments. Nevertheless, such a barrier can lead to a rise in groundwater level. Destabilising of the slope can therefore occur due to the reduction of effective stress. In an opposite task, when a pile wall is filled with pervious gravel instead of concrete, it can work as an underground drainage wall.

4.2.3. Grouting

Grouting covers different injection techniques of special liquid or slurry materials called grouts into the ground for the purpose of improving the soil or rock. Different types of grouts exist. The most common are cement grouts made of Portland cement that hydrates after injection to form a solid mass and chemical grouts that include a wide variety of chemicals which solidify once they are injected into the ground.

Grouts are used to cut-off fluids and increase shear, tensile or compressive strength of structures and soils. Another common use of grouts is for waterproofing structures or the containment of air-born contaminants. The liquid or suspension can be injected either by drilling, driving down pipes or by jetting.

Depending on the different tasks and the operating ranges required, a distinction can be made between intrusion grouting, permeation grouting, compaction grouting and soil frac grouting.

Jet grouting is a special technique that mixes up soil and suspension in the sub-ground by extremely high pressures.

Intrusion grouting consists of filling joints or fractures in soil or rock by injecting grout through pipes. Its primary benefit is the decrease in hydraulic conductivity.

Permeation grouting injects thin grouts into the soil so that they penetrate into the voids. Once the soil cures, it becomes a nearly solid mass. Most permeation grouting is done using chemical grouts, as these can be thinner than cement grouts and thus enter the voids more easily. It is often used to form groundwater barriers and to stabilise soils in advance of making excavations or tunnels.

Compaction grouting uses a stiff grout that is injected into the ground under high pressure through a pipe to form a series of inclusions. The suspension is too thick to penetrate the pores, but the inclusions compact the adjacent soil. This is often used to repair structures that have experienced excessive settlement.

Jet grouting uses a special pipe equipped with horizontal jets that inject grout into the soil at very high pressure. Pipes are first inserted, then raised and rotated to form a column of liquefied soil and cement suspension that will harden to a soft concrete column. The method is usable on a wide variety of soils and has been used on a wide variety of applications to reduce seepage under dams, to increase the strength of weak soils for structural support, to reinforce unstable land masses or to rehabilitate and reinforce structures.

4.2.4. Muckshift

Muckshift can be described as the excavation and exchange of unsuitable soil regions by more qualified ones. It is a kind of large scale land clearance. Equivalent to rock facing, muckshift provides the stability of tailings impoundments, the drainage and consolidation behaviour inside tailings impoundments. In this way, the height of the phreatic line can decreased. Muckshift can be defined as the restoring of existing soils in one working step with the following applications:

- Strengthening the tailings dam foundation if there are weak soil layers existing between an impermeable ground layer and the further dam contact area.
- Possible thin clay layers between the coarse materials in the beach area following wrong inflow technology or observation failure can be partially replaced with the aim of reducing the phreatic line.

Another kind of muckshift is the installation of interim layers for loading the tailings impoundment and accelerating the consolidation phase.

4.2.5. Sandbagging

Sandbagging, in the context of tailings dams, is an engineering prevention method against tailings dams engineering failure. Sandbag dikes can prevent or reduce overtopping during flooding or a storm. The dike is built up on the tailings beach or sometimes on the tailings crest, when the reliability of the dam is known. The seepage is especially observed, so that no dam failure can occur. Furthermore sandbags can be used for preventing a leachate discharge downstream of the embankment site. Together with filter materials or woven or non-woven geotextiles, sandbags will be used for burdening with the aim of shrinking the seepage. The sandbags will be laid from the dam toe up to the crest (Figure 40).

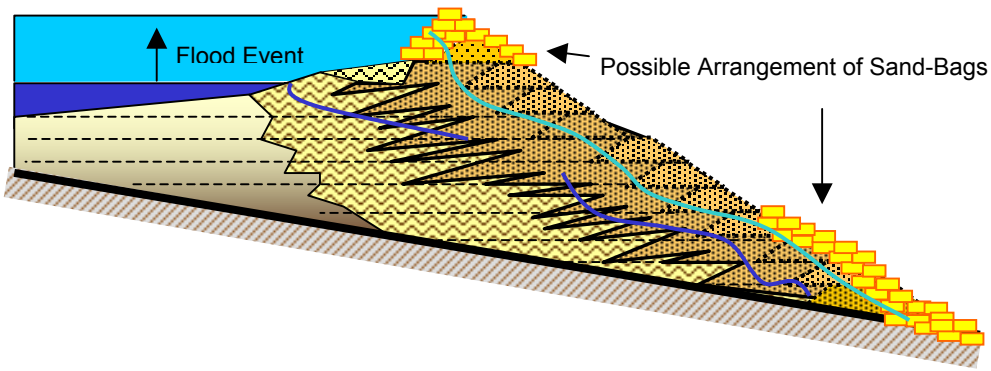


Figure 40: Possible arrangement of sand-bags for strengthening of an upstream tailings dam.

In practice we can use jute or plastic sandbags, the sandbag-couple and improvised sandbags. In different countries the dimensions and the maximum weight are standard.

4.3 Geosynthetical structures

Geotechnical structures can be used to ensure geotechnical safety when covering tailings, especially soft tailings. After the removal of the water in the beach and pond a capping system can be placed to increase the bearing capacity of the material, to reduce infiltration or to guarantee the future use. For instance in addition it would be possible to bring up interim layers for accelerating the consolidation and to provide a safe basis for carrying out essential reconnaissance and stabilisation measures. In zones consisting of soft tailings, the undrained shear strength near the surface can be less than 5 kN/m². Geotechnical structures involving geotextiles are adequate solutions in remedial strategies to optimise the cost-effective ratio. Therefore it is necessary to develop a comprehensive experience of the characteristic tailings behaviour under typical impacts, especially for soft cohesive soils. In addition to load-deformation investigation the shear strength behaviour of the whole impoundment must be determined. This is to avoid a failure that can occur during covering work. The use of geosynthetics is necessary for a variety of technological and remedial reasons.

4.3.1. Non-woven geotextiles

Non-woven geotextiles are manufactured for subsurface drainage, roadway separation, railway stabilisation, hard armour underlay, asphalt overlay, geomembrane protection, gas venting and drainage systems [20]. To distinguish between Polypropylene (PP) and Polyester (PET) non-woven geotextiles. PET Non-woven Geotextiles are similar in application to the Polyproylene Non-wovens with the primary difference being the polymer type used.

In impoundments of settled sediments, non-woven geotextiles will be placed as a separating layer between the tailings material and interim layers to prevent the deposited mass from rotational failure or slumping. This type allows the preliminary accessibility to the site. Natural consolidation of the surface trough evaporation and desiccation will be contributors to increased occupational safety. The excess water can be removed as fast as possible. Non-woven geotextiles are excellent filters, allowing subsurface water to pass into the drainage core while preventing adjacent soil from clogging the system. Furthermore they show a good chemical compatibility with various leachates and allow lateral transmission of liquids and gases that may build up beneath flexible geomembranes used in the closure and capping of waste facilities.

4.3.2. Geogrids

Geo-grids are a geosynthetic material of connected parallel sets of tensile rips made from polymer with apertures of sufficient size to allow strike trough of surrounding soils in a mesh or grid form. They are manufactured in various ways to provide strength by providing an interlocking system for rock and soil. The primary function of geogrids is clearly reinforcement. In tailings impoundments it is essential for remedial work that the fine slime tailings are accessible after the pond water level is drawn down. Geogrids are very light but have an inherent rigid structure. So single loads in slime areas can be spatially distributed and because of the plane load bearing effect, a balance can be generated. The plane load bearing effect can be named as “snow shoe effect” [24]. Decisive is the torsion rigidity in the direction of the load. The resistance moment increases to the power of 3 with the thickness of the rod. The joint rigidity is insignificant against the rod dimension, because the flexural strength of a geogrid is the product of the moment of inertia and its elasticity modulus.

Using geogrids together with non-woven material the trafficability on extremely fine slimes can be guaranteed. For this aim combined products also exist [84].

4.3.3. Vertical wick drains

Consolidation of soft cohesive soils using prefabricated vertical drains (also called wick drains or band drains) can reduce settlement times from years to months. Wick drains can be used for dams, large storage areas, highway embankments, sedimentation ponds, tanks, bridge abutments, buildings, and airport runways. Consolidation of slimes or fine tailings material occurring as pore water is squeezed from the soil matrix under the force of gravity or under additional layering at the cover.

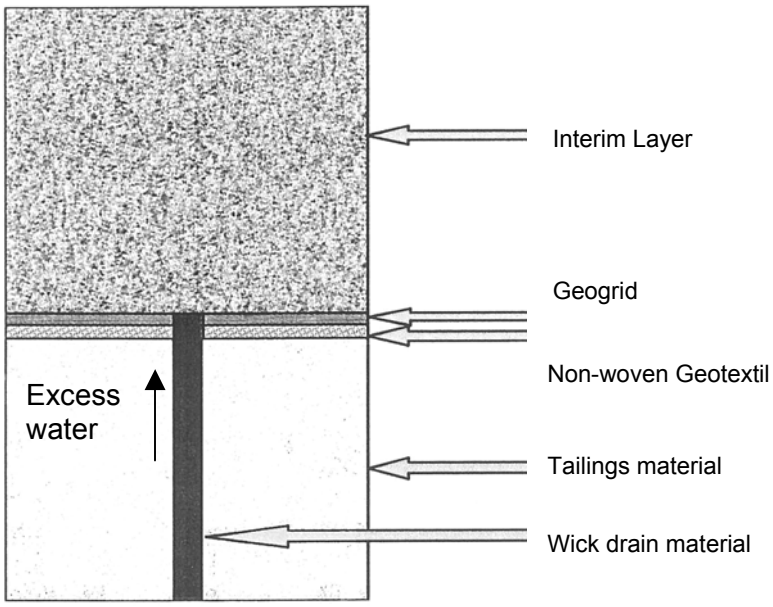


Figure 41: Function mechanism of wick drains.

The effectiveness, especially the time for consolidation, depends on the square of the distance of the strips. The installation of prefabricated vertical drains provides shortened drainage paths for the water to exit the sediment. The prefabricated vertical wick drain core is made of high quality flexible polypropylene which exhibits a large water flow capacity in the longitudinal direction of the core via preformed grooves or water channels on both sides of the core. Each vertical wick drain can provide a greater vertical discharge capacity than a 15 cm diameter sand column. The prefabricated vertical wick drain core is tightly wrapped in a geotextile filter jacket of spun-bonded polypropylene which has very high water permeability while retaining the finest tailings particles. Both the core and geotextile filter jacket have high mechanical strength, a high degree of durability in most environments, and high resistance to chemicals, micro-organisms, and bacteria. With the integration in soft tailings impoundments a reduction of excess pore water pressure can be reached as well as significant increase of the undrained cohesion.

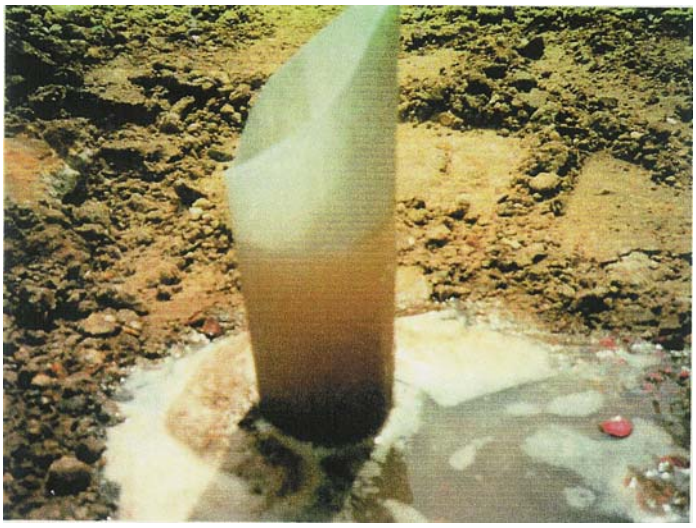


Figure 42: Water from fine tailings using wicks drains
(Source: http://www.geotechnics.com/vertical.htm).

The resulting stabilisation of the upper tailings layer is a decisive prerequisite for the construction and reliability of a capping system. The vertical wick drains are usually placed in a triangular configuration of 1 to 4 metres, depending on the desired consolidation time.

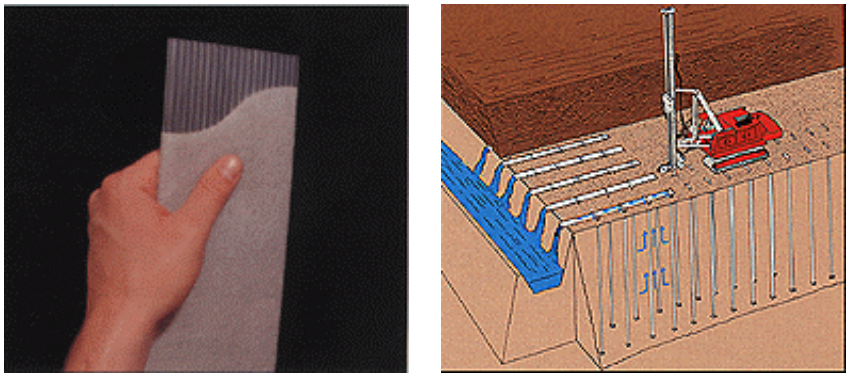


Figure 43: Arrangement of vertical wick drains in tailings impoundments
(Source: http://www.americandrainagesystems.com/wickdrain2.htm).

Nevertheless the initial strength must allow the trafficability of the equipment during construction.

The wick drains are a further development of vertical granular drains, like sand drains. Sand or granular columns may also be used to provide vertical drainage, depending on the type and nature of the soil. The granular columns will be integrated by dynamic loading or ramming. If only in surrounding noncohesive weak soils the granular columns will be jacked with permeable geotextiles, so that they are stable.

4.3.4. Horizontal strip drains

Horizontal strip drains (horizontal drains) are prefabricated, a high-flow soil drainage system that offers better draw-down of water than pipework while costing around 60% less to install. Strip drains consist of a formed polymeric core surrounded by a geotextile filter fabric (Figure 44). The filter fabric allows water to pass into the core while restraining soil particles which might clog the core. The core allows water to flow to designated drainage exits. The strip drains have a low installation cost and a high flow capacity. They are easy to handle, strong and durable and chemically resistant. Their advantage in tailings impoundments is to accelerate the process of consolidation and to work against anisotropic pore pressure conditions.

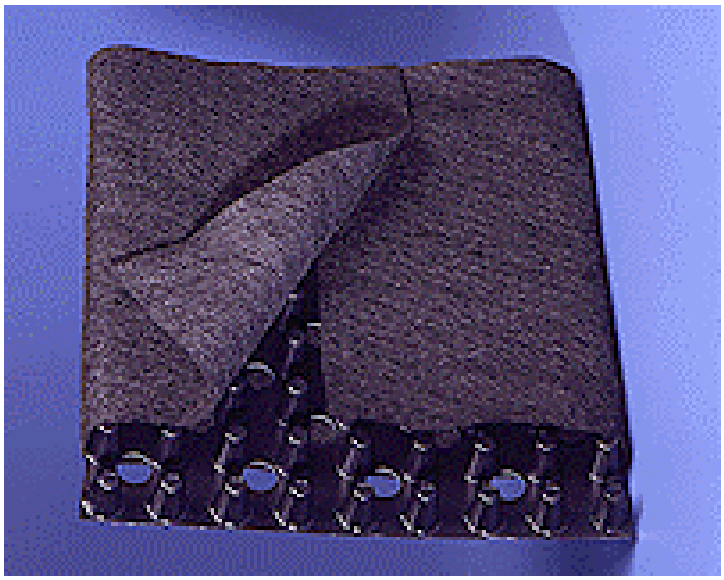


Figure 44: Horizontal strip drains in tailings impoundments
(Source: http://www.americandrainagesystems.com/stripdrain2.htm).

4.3.5. Geofabric sand mats

Geofabric sand mats are used for protecting the surface against environmental impacts like wind and water erosion or release of pollutants trough slip movement. Furthermore they can be used as separators and filters in hydraulic engineering applications. The major application is to protect upstream slopes of embankments against wave forces. But sand mats can also be used as a part of a capping system in case of a low strength of the sediment.

Figure 45: Arrangement of sand mats on an embankment slope [126].

4.3.6. Geonets and other geocomposites

Polymer nets of various thickness and comprehensive strength are combined with geotextile filters resulting in extremely efficient flat drainage panels for liquid and gas. The producers of geosynthetics are able to design products for specific drainage and strength demands, so that geocomposites can apply in a wide range of other mechanical tasks.

4.4 Methods of dewatering

Dewatering of tailings is important not only for receiving a more stable surface for following earthwork but for protection of groundwater quality in the vicinity of tailings ponds. Drainable water from tailings sooner or later will seep into the ground causing contamination of the groundwater in case of polluted excess water. Tailings ponds usually consist of two main parts: dam section, which is responsible for the stability of the tailings impoundment and pond section.

Dewatering is a method of improving the soil properties by reducing the water content and/or pore water pressure with the aim of water management of tailings inflow and outflow in the context of possible hazardous events. Therefore many site-specific decisions are necessary. For example in the reclamation term the following actions are possible:

- Removal of the free water
- Stabilisation of the impoundment
    - De-watering the fine tailings
    - Repairing the drainage system
    - Covering the geotechnically stable piles
    - Re-vegetation of the covered piles
- Water treatment

Dewatering is strictly concerned with the decrease of phreatic level and the free water level. In this sense dewatering means a reduction of moisture content in tailings materials by physical reaction, and a decrease of the groundwater pollution as a chemical reaction. Hence the methods of dewatering increase strength.

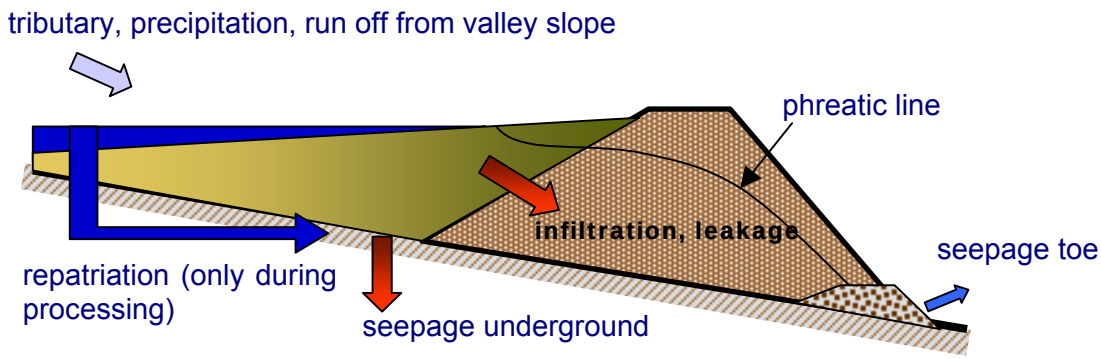


Figure 46: Water flow balance system in tailings facilities.

For dewatering of tailings impoundments different methods and system components exist. Decant systems and diversion channels can be mentioned as import components.

Decant systems are generally used in conjunction with other forms of surface water control. Major costs associated with the decant systems are those of pumping, maintenance and treatment. It may be difficult, in areas with large surface water runoff volumes, to provide enough wells for removal of the runoff in a timely manner.

Diversion channels can be used for most dam designs, especially valley-bottom dam designs. Closed channels are usually used under cross-valley dams because they generally do not permit a side channel for diversion. Water treatment is not an issue with diversion channels if they begin diverting the runoff above the dam. However, the long-term reliability of diversion channels as well as the maximum probable charge must be considered in design.

In the following the different methods of dewatering are explained. In the detailed description only the mode of action on the phreatic line, seepage and the moisture content is considered.

4.4.1. Dewatering by wells

Pumping methods are most appropriate for the majority of coarse and medium soils. Wells have a varied operation area relating to the task of dewatering. They can be arranged

- around the tailings facility to influence the tributary of groundwater,
- inside the tailings impoundment to reduce the phreatic level, or
- on the tailings dam's toe for reducing possible groundwater pollution through tailings contaminants.

The arrangement of wells in the catchment area of tailings facilities reduces the tributary of groundwater in the impoundment. Combined with drain systems, drainage ditches or trenches (outlet ditches, diversion channels or dikes) and possible open mine pits, the superficial tributary can be deflected around the tailings facility. It follows that the groundwater pollution downstream of the tailings facility can be deflected or avoided, especially for cross-valley, sidehill and valley bottom impoundments. Tailings facilities bounded by ring dikes do not have a catchment area for additional tributaries.

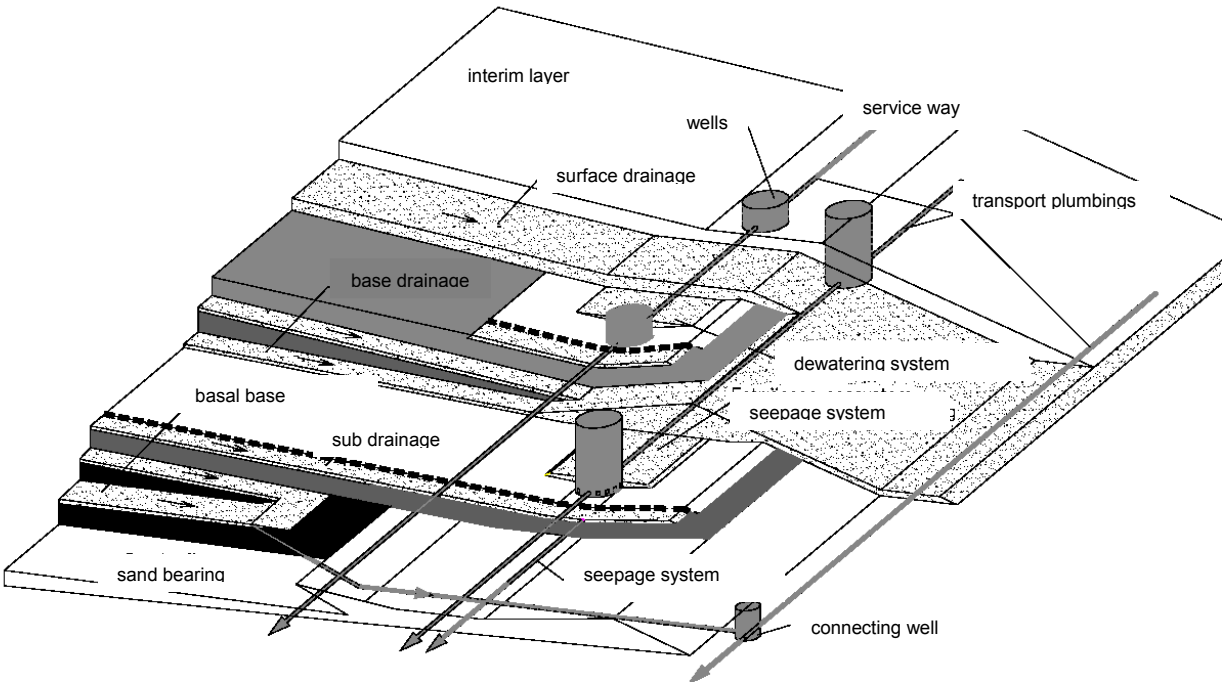


Figure 47: Possible arrangement of wells inside a tailings facility [16].

An important task for the rehabilitation and long-term behaviour of tailings impoundments is the acceleration of consolidation and the early caused settlements. The design and construction of drainage and covering systems as well as the start of after use measures depends on this. For reducing the (i) the phreatic level, (ii) the amount of contaminated tailings water and (iii) the free water level during hazardous floods and storms, dewatering wells can be assigned inside the tailings impoundment. Vertical and horizontal wells covered with permeable material and geosynthetic structures are proper solutions for these aims. These applications are unusual. Normally a wide range of possible drainage actions exists. Two requirements are acceptable (i) dewatering by wells works only in coarse grained subsoil and (ii) dewatering by wells is usually a self regulating system, but it needs energy for the whole period of application.

In old tailings facilities, engineering methods for design, construction and monitoring are not well developed, a release of contaminants in groundwater can happen. The same scenario of contamination is derived from failure of the drainage system inside the tailings facility. The polluted water can’t drain off through the applied pipe system. The pollutants are detached in seepage water and contaminate the groundwater. Therewith the pollution can not progress and interact with groundwater catchment areas for flora and fauna. As a further solution, a series of new wells can be arranged against the flow direction on the corresponding tailings impoundment border. The treated water can discharge to a tailings pond.

Beside the classical application of wells a wide range of special applications exist. Figure 47 shows a combined dewatering system with drainage layers, transport pipes and deep wells. Other intelligent systems are diversion wells and reactive wells, which initiate a water treatment when water is passing the reactor. Diversion wells add alkalinity to contaminated waters. In diversion wells acidic water is diverted vertically through a pipe from an upstream dam to a downstream "well" containing crushed limestone aggregate. The most common application of reactive wells technology is to mix zero-valent iron metal with the filter pack sand to create a reaction zone. The iron would reduce contaminants such as chlorinated solvents and some metals including chromium and uranium.

4.4.2. Dewatering by loading

Soft tailings and tailings with fine graded cohesive material need a relatively long consolidation time. The expected settlements don’t occur suddenly but over a long time. The dewatering time of soft material depends on the present pore water pressure, the permeability and flow distance to the next drainage surface. Due to the low overburden pressure gravity induced consolidation will not appear on the upper region of the pond. From this, one of the most important tasks is the stabilisation of fine tailings, which have a very low bearing capacity especially in the upper

part. The low surface strength can lead to failures during the application of the covering and as a consequence the sinking of the covering layer (and in the extreme situation working equipment) in the fine tailings. This work can only be carried out when the surface of the tailings is stable enough for the planned technical equipment to install the interim loading cover.

The primary aim of the stabilisation of soft tailings is to provide safe conditions for covering of the tailings ponds. All investigations performed show that the undrained shear strength of the tailings is an essential parameter for the assessment of the bearing capacity of the fine tailings. When additional loads impact the tailings surface, the pore water pressure will be increased in time. Following the exceeded pore water pressure there is a trend to a lower potential so that the stress equilibrium will be reached. This is only possible if pore water flows out on to the next drainage surface. The overburden loads are increased over a determined time frame. If the loadsteps are too high and to fast, then pore water pressure tends to be equal to total pressure and the effective stress is zero. The result is soil liquefaction and therefore problems with bearing capacity.

Practice of stabilisation and dewatering of fine tailings is well established. This is due to the huge volume of fine tailings in the mining industry. The grain size distribution of the tailings being deposited has become very fine over the past decades in some industries. The process starts with elimination of free water from the tailings ponds. After this the surface of fine tailings is exposed to weather conditions and in most cases a desiccation process takes place.

Desiccation is a gradual process, which leads to the significant increase of shear strength on the upper layers (~0.2-0.5 m), reaching the requested minimal value of 5-10 kN/m^2. The next step is a careful placement of the first interim cover, which has to be water conductive for leading the deliberated water under the pressure of loaded material. The next loading layer can be placed only after dissipation of the excess pore water pressure (or most of it) caused by the placement of the first layer. Figure 48 shows the effective stress and excess pore pressure in relation to the initial and final effective stress (consolidated state) under loading fine tailings [49]. In order to enhance the dewatering process in comparison with normal gravity drains, wick drains are frequently used.

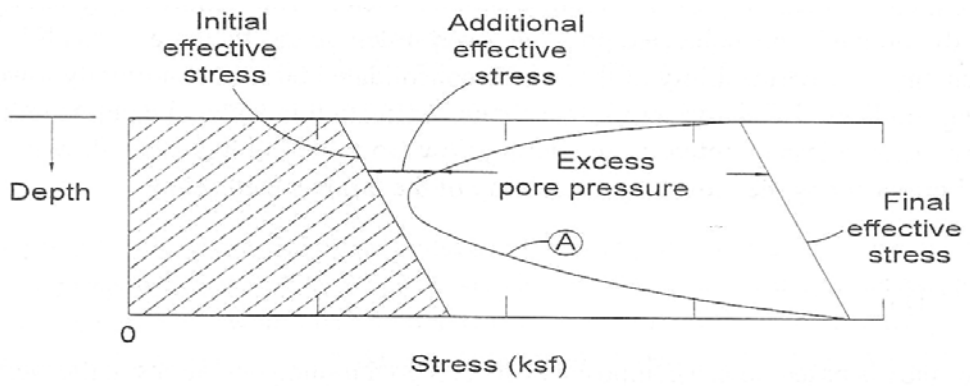


Figure 48: Effective stress development after installing interim layers [49].

4.4.3. Dewatering of the dam structure by horizontal drainage

The drainage system in tailings impoundments has to guarantee (i) a low phreatic surface (ii) a reduction in hydrodynamic pressure deforming the flow net (iii) reduction in pore pressure (iv) control of phreatic line and non-migration of tailings particles. With a low phreatic surface is it possible to assume that seepage does not emerge on the downstream slope, the hydrodynamic pore pressure is minimised and that a large section of the tailings dam can be more easily desaturated.

Directly over the drained soil layers, the soil is unsaturated. The mass of the saturated soil above provides increased resistance to liquefaction and increases the rate of consolidation. With the decrease of the hydrodynamic pressure despite a high phreatic line, the flow net shows equipotential lines tending toward the horizontal, so that the hydrodynamic pressure is zero.

The pore pressure in tailings impoundments develops due to the load of the overlaying material. Using drainage systems the mass of the overlaying material is decreased and the consolidation is accelerated. Summarising this, the drainage system is designed for draw down of the phreatic line and to get nearly horizontal equipotential lines, that then results in a vertical flow instead of inclined seepage force.

As stated above, filters must be incorporated in the design at the interface between zones of significantly different permeability both within the dam and its foundation. Dependent on the percentage of fines in the tailings, especially the clay content and the site conditions, different dam construction methods are required.

Tailings dams of water retention type

This construction type is often used, when loss of effluent is to be avoided. This is the problem when tailings are very fine and toxic, ecological requirements are strict and the impact of dynamic loads is possible. Three basic options are shown in Figure 49.

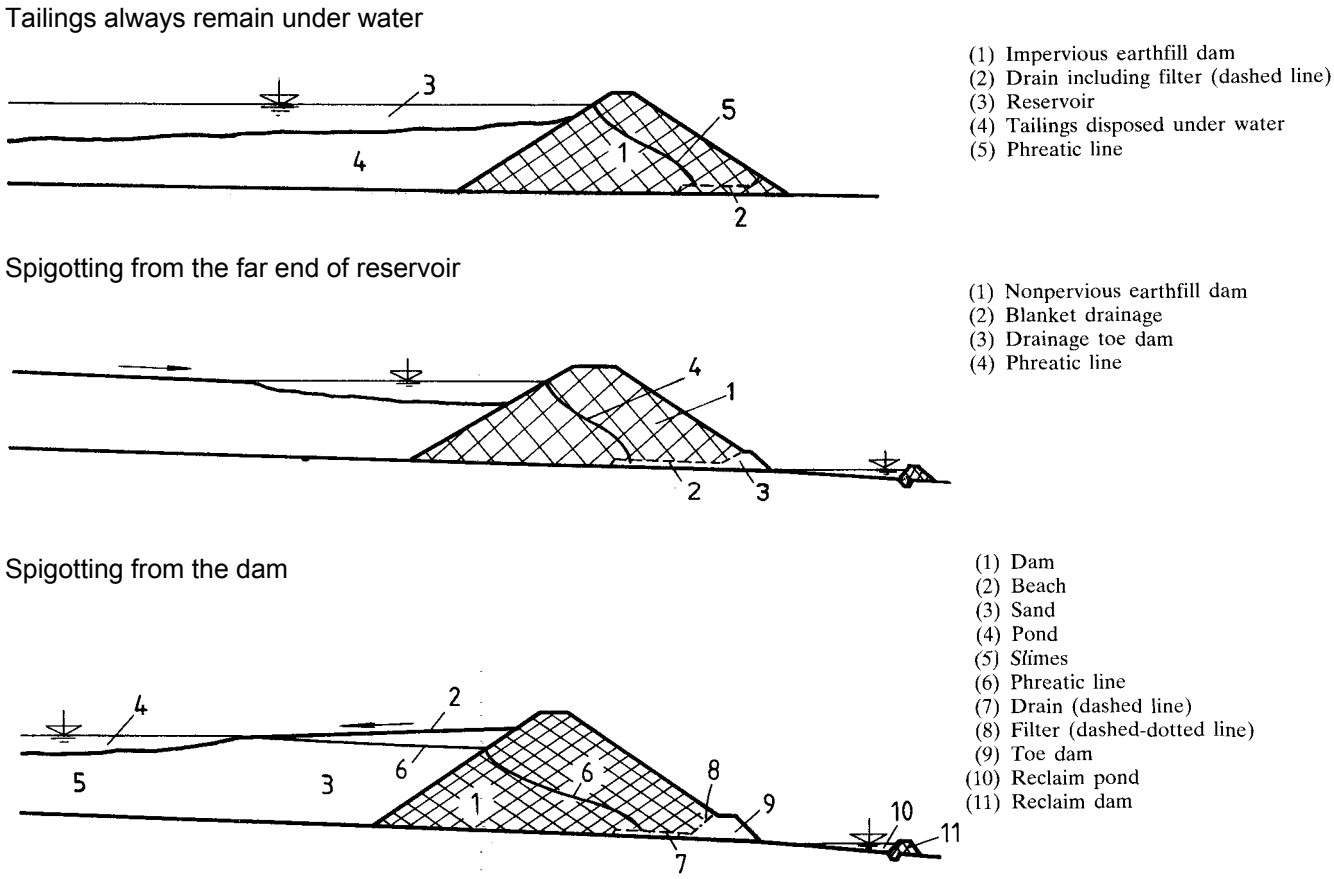


Figure 49: Basic water retention types [53].

The tailings material is deposited under water, so that dust pollution is not possible. The permanent water level guarantees no erosion effects. In the second case the slurry is spigotted from the far end of the tailing facility in a downstream direction toward the dam. The pond water is near the dam construction, so that the reliability of this method depends on the dam itself. The phreatic line is higher than the other cases, but the dam height is lower. In the third case the slurry is deposited by spigotting near the dam crest in an upstream direction. The coarse material is deposited near the dam, which increases the stability and permits a steeper slope in comparison with a conventional earth-fill dam. Like in any homogeneous earth fill dam for water retention, a continuous drainage layer is arranged on the downstream toe in the foundation level. As seen in Figure 49, the drain ensures that the phreatic line is always inside the dam

construction. The method of depositing affects the dimension of the drainage layer in terms of thickness and length from upstream to downstream toe. A conventional design is necessary.

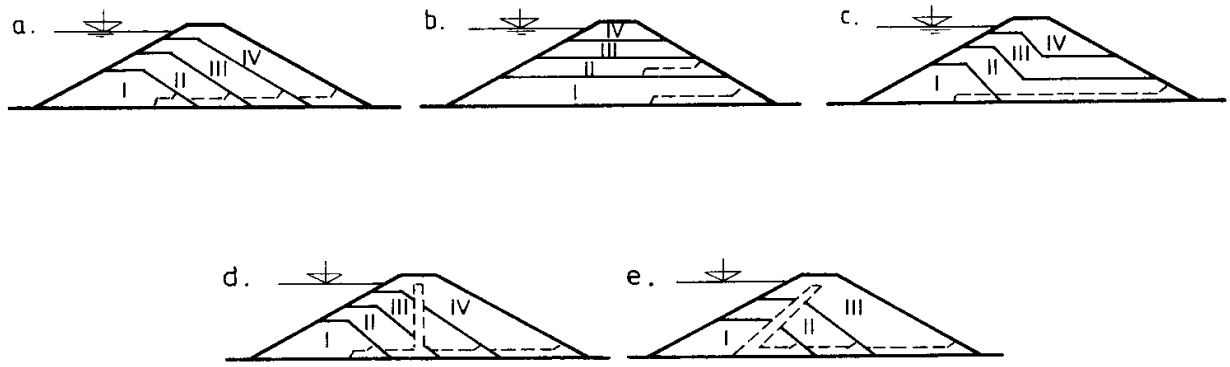


Figure 50: Construction stages - homogeneous dams and dams with wall drains [53].

In Figure 50 typical construction stages and drainage arrangement for earthfill dams are shown. In every case the design has to consider the conditions of drainage as well as the filter requirements. A filter zone must be placed on the upstream face for preventing migration and piping.

Tailings dams of upstream construction

The upstream construction method is probably the most common construction method for tailings embankments. This method uses deposited coarse material near the dams for raising them. Normally a wide non-submerged beach exists between the dam crest and the pond. If spigot flow is correct, the particles are graded from coarse to fine in the flow direction. The success of these construction methods depends on a significantly wide beach of coarse tailings. The main disadvantage is that layers with coarse materials overlay zones with fine material, which consolidate slowly so limiting the height of the dam. These disadvantages can be overcome with improved stability in parallel with increased dam height safety through an arrangement of appropriate drainage systems.

When using starter dams with high permeability, it should be ensured that no tailings material infiltrates into the dam material. Therefore a filter layer on the upstream side to the drainage is necessary. Furthermore it should be ensured that the filter material does not erode or slump due to rainfall or spigotting. To avoid this it may be necessary to flatten the slope of the upstream face of the starter dam. Normally it is not possible to avoid fine tailings being placed close to the starter dam. When spigotting starts the settling pond is quickly submerged. Until the first

spillway start, the fine grain particles are deposited on the drainage blanket, so that the drainage blanket does not work and a zone of poorly drained, low strength slimes remains to consolidate slowly and provide a weak foundation for overlying construction.

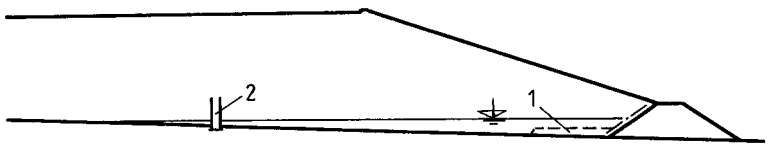


Figure 51: Upstream blanket drainage under water:
(1) Upstream blanket drainage under water; (2) First decant tower [53].

It should be ensured that an efficient drainage blanket is built up above the initial pond level and never subsequently submerged. Therefore the upstream tongue is constructed of the same or similar material as the starter dam. The tongue should be higher than the possible water level. The length and the chosen material type shouldn't decrease the stability of the whole construction.

If the starter dam consists of low permeable material, additional drainage facilities are necessary. If permeable soils are not available, only low permeable materials should be used. If specific drainage features are not incorporated in the design of the starter dam, the soil will remain saturated and the phreatic line will emerge onto the slope. The drain can be placed on the upstream slope and the filter or drain system is extended along the ground under the starter dam (Figure 52).

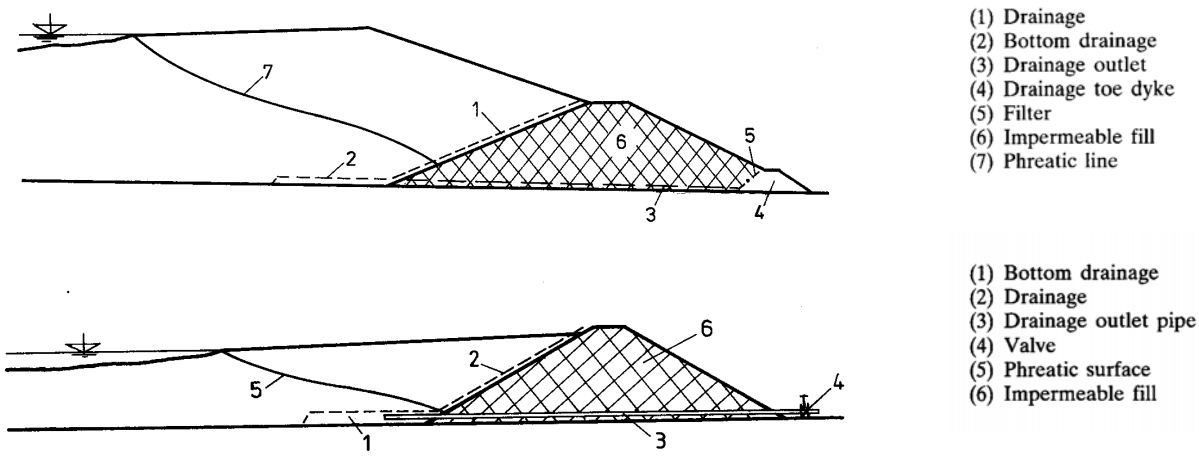


Figure 52: Earthfill starter dam with drainage outlet / drainage outlet pipe [53].

In the arrangement on the base of the starter dam, the drainage system can be lifted to a determined level on the upstream site, so that the stability is ensured.

For the upstream construction method the different raise levels are built up from tailings materials deposited on the tailings beach. Here coarse to medium sized sand or alluvial sand-gravel mixtures are preferred. Dams made of this material are free draining and do not require any drainage measure. But, if the deposited tailings materials are fine grained, these drain slowly.

For raising the dam, borrowed material i.e. rockfill, is necessary. As before in the contact zone between fine tailings and rockfill, a filter layer is integrated for prevention the sinking of rocks and migration of fines into the permeable zone. The installation of the drainage requires a dry beach. If this is not possible mechanical devices can not be used. Alternatively, a controlled spigotting can be used, so that the permeable material is hydraulically spread. When the dam is built of very fine tailings, a flat downstream slope is required in order to maintain sufficient overall stability. Filters in the drains can be built up at the same time (Figure 53).

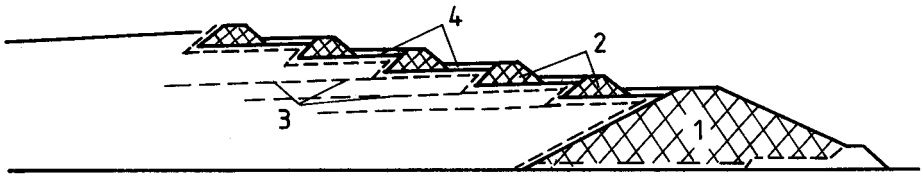


Figure 53: Impermeable dykes at a flatter slope [53].

From an economic point of view, instead of secondary dykes, the downstream slope can be surcharged with mine waste simultaneously as the waste arises.

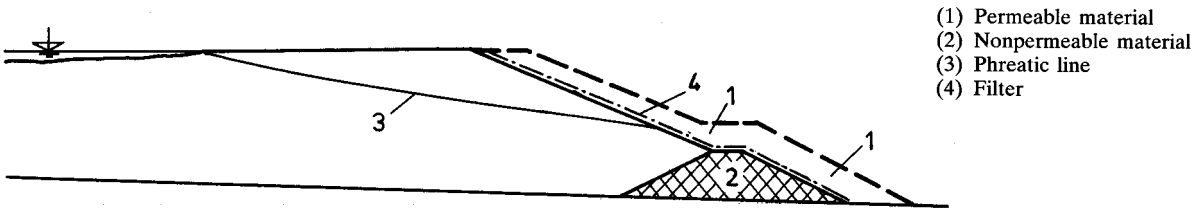


Figure 54: Nonpervious starter dam [53].

Again in the case of fine tailings a normal inclined downstream slope can be constructed, when incorporating strip strains. These drains are made of free draining gravel surrounded by a soil filter or geotextile (Figure 55). Other methods are (i) spigotting sideways from the abutments to produce layers of sand size material or (ii) the construction of interconnected continuous drains with discrete horizontal outlets spaced at specific intervals.

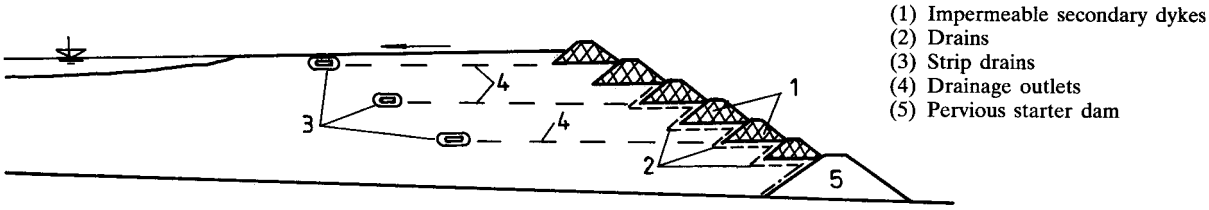


Figure 55: Use of strip drains [53].

The vertical drains are constructed by trenching and replacing the fine tailings with coarse or medium sized material, which acts as a filter and drain.

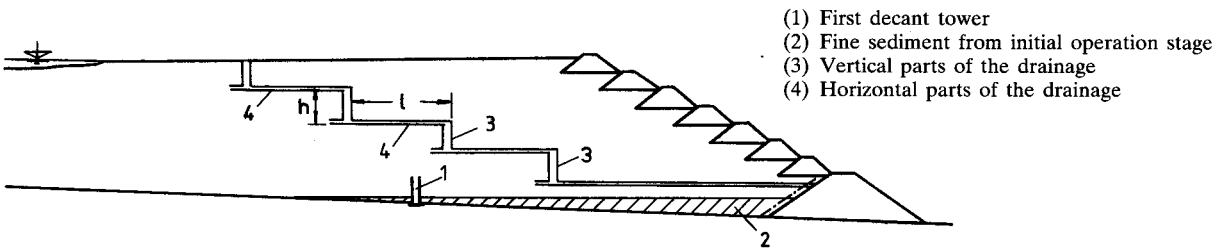


Figure 56: Use of wall and blanket drains [53].

The coarse grained sand fraction from cycloning near the dam crest provides a good material for constructing the downstream zone. As previously mentioned, this material can be used as a filter and drain simultaneously. Additionally, it is a suitable material for a toe weighting berm increasing the stability of the dam construction.

Tailings dams of downstream construction

The sand for raising the dam is obtained from cyclone operations, and is the cycloned overflow. The sand has a high permeability, so that only minimal drainage features are required at the foundation level. As well as the drainage there can be a bottom soil layer from the starter dam

to the downstream toe, or an equivalent network of fine finger drains trenched into the foundation. This construction method causes high settlements in the embankment without mechanical compaction.

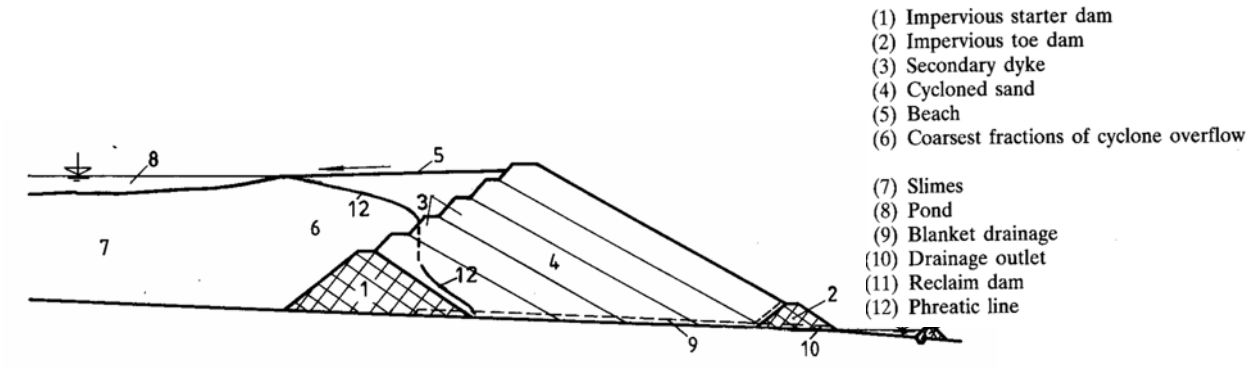


Figure 57: Tailings dam of downstream construction [53].

For this embankment specific drainage measures are necessary, particularly above foundation level depending on grain size and permeability of cycloned sand. Usually the whole foundation surface of the cycloned sand section should be drained. The downstream toe dyke can be constructed either from pervious or impervious material. If impervious material is used a drainage system under the toe dam is necessary. The drainage function can be underlain by continuing the foundation drainage layer under the reclaim dam. Compacting of cycloned sand layers will not only make it remarkably rigid but also reduce its permeability.

Tailings dams of centerline construction

The drainage methods and systems in these structures are the same as in the downstream construction type.

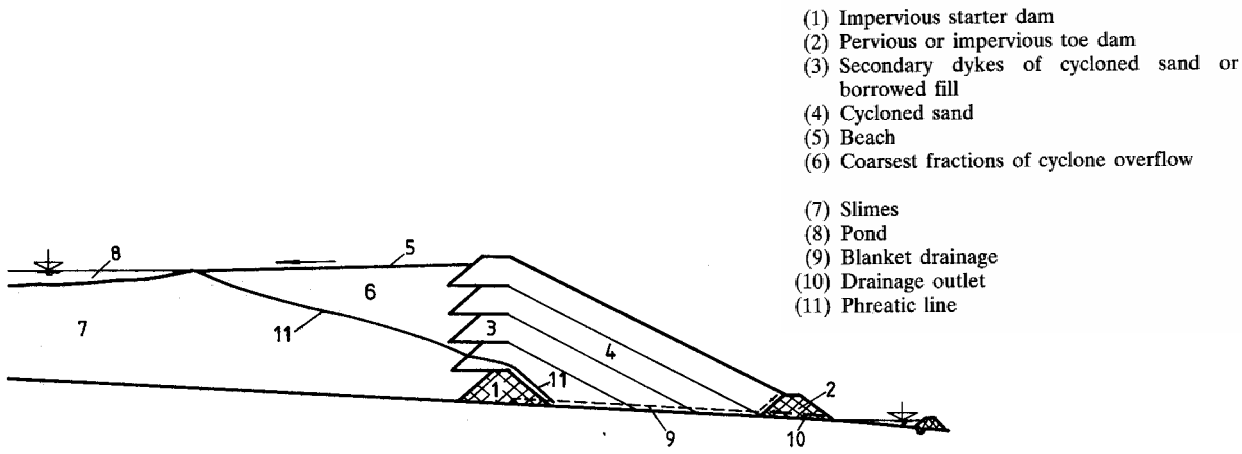


Figure 58: Tailings dam of centerline construction [53].

4.5 Covering

4.5.1. General remarks on Impacts and vegetation covers

Immediately after discharged ceases the lagoon surface will consist of a relatively firm and dry sand beach, a soft and saturated slime surface and a submerged area covered by the decant pond. To prevent any erosion by water and wind during the early stages after deposition, the lagoon area can be closed with a geotextile, a surcharge of free draining fill is then applied to cause surface emission and consolidation of tailings materials. In addition, a chemical stabilising agent can be used for temporary erosion control, but it can not be considered as a permanent reclamation measure.

- Another aspect of using a cover system is the protection of the environment against chemical reactions and there potentials to release contaminants. Furthermore, dry cover systems avoid the inflow of surface water as well as infiltration from precipitation. The moisture content and the phreatic level can then decrease, together with the risk of failure of the tailings impoundment. The most likely events that can induce failure of tailings impoundment designed for the long-term phase are overtopping by extreme hazardous floods. In areas, where the precipitation exceeds the evaporation or in general where the climatic and topographical conditions are suitable, consideration should be given to permanently flooding the surface of the closed tailings deposit with water. This will create an effective long-term seal against the ingress of oxygen into the deposit and hence inhibit the weathering process that may lead to the formation of acid. The long-term stability of a flooded deposit will require consideration of the following [55]: an under water deposit must have an adequate catchment area to guarantee a permanent water cover of the tailings. For this reason it will probably be necessary to locate the deposit in a valley
- the stability of the tailings embankments must assure that the probability of slope failure is reduced to an acceptable level
- the dam should be designed to withstand extreme events such as Probable Maximum Flood (PMF), Maximum Credible Earthquake and high wave actions
- the dam should be designed to prevent long-term deterioration induced by erosion, ice and frost forces as well as other weathering. Where feasible, soil and rock materials possessing favourable long-term resistance to weathering should be used to support fill
- the phreatic surfaces within the dam should be controlled by adequate drainage to ensure dissipation of excess pore water pressures.

In areas, where the evaporation exceeds the precipitation the danger against surface erosion by wind is very high. Vegetation is by far the most common and usually the preferred stabilisation option for this.

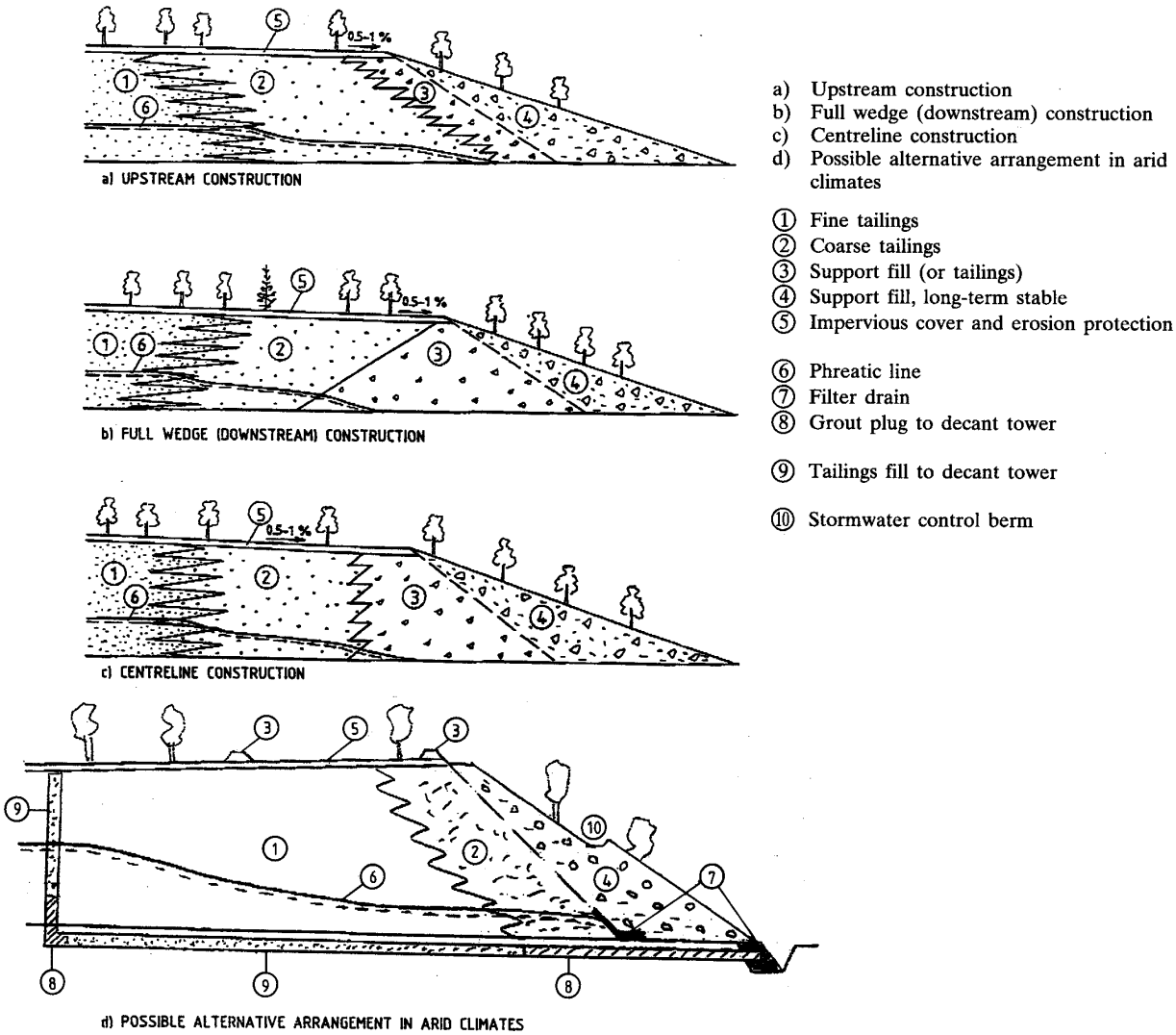


Figure 59: Typical dams for dewatered deposits [55].

Different vegetation systems can be installed here as an erosion protection system depending upon the nature of the growth medium.

Table 5: Examples of plants for the reclamation of tailings facilities [103].

Species	Varieties	Erosion control	Deep reinforcement	Water removal	Comments
Grasses and sedges	Common bent	X			Wide soil tolerance, some varieties tolerant of heavy metals
	Couch grass	X			Not tolerant of extremes
	Creeping red fescue	X			Very wide soil tolerance, some varieties tolerant of heavy metals and salt
	Flattened meadow grass	X			Tolerant of very infertile conditions
Legumes	Crown vetch	X			Wide tolerance, slow to establish
	Birds-foot trefoil	X	X		Wide soil tolerance, salt tolerant
	Alsike clover	X	X		Tolerates waterlogging
Trees	Common alder		X	X	Suitable for wet sites and derelict land
	Birches	X	X		Tolerant of infertile conditions, good pioneer species
	Hawthorn		X	X	Wide soil tolerance, salt tolerant

The characteristics that strongly influence vegetation growth are texture, fertility and toxicity. Texture affects the degree of aggregation of particles and the water retention capability. Tailings sands have low moisture retention behaviour. Slimes are less aerated and become compacted on drying. Soil fertility is reflected by the availability of nutrients as well as the necessary bacteria and fungi. High levels of toxicity and salinity kill developing plants, although some heavy metals support the health of plant growth.

Table 6: Possible grass based seed mixtures [%] for site revegetation [21].

Species	Site prone to waterlogging	Site prone to drought	
		Acid conditions	Alkaline conditions
Timothy	10		
Smooth meadow grass	15		20
Rough meadow grass	10		
Flattened meadow grass	5	30	10
Creeping red fescue	40		55
Sheep's fescue		30	
Browntop bentgrass	5	10	
Creeping bentgrass	10		10
Wavy hair grass		25	
White clover	5	2.5	2.5
Birdsfoot trefoil		2.5	2.5

4.5.2. Overview over the most commonly used cover systems

One of the main issues related to mining activities is the occurrence of polluted water from chemically toxic mine wastes and waste rock dumps. In this process, the residues will be deposited in slurry form in tailings facilities. This problem is common at mine sites.

For example pyrite is frequently associated with minerals like coal, gold and uranium. Hence the mechanism that leads to pollution generation is the oxidation of sulfides that occurs when the reactive pyrite present in the waste comes into contact with oxygen and water, so producing acid water.

Methods to provide isolation and control of radiological, oxidation, leaching effects and for increasing erosion protection against water and wind can be divided into the following categories:

- Wet covers
- Dry cover
- Vegetation cover as a special form of dry covers.

Water covers provide the most effective control of sulphide oxidation rates. Soil covers can only approach the efficiency of water covers when a proportion of the cover material remains saturated, so reducing the diffusion rate of oxygen through the cover. However, soil covers also offer the advantage of reducing the water flux/transport medium through the material.

4.5.3. Dry (vegetation) covers

Dry covers can be simple or complex, ranging from a single layer of earth material to several layers of different material types, including native soils, non-reactive tailings and/or waste rock, geosynthetic materials, and oxygen consuming organic materials. Types of single layer covers are shown in Figure 60.

Multi-layer cover systems (Figure 61) typically utilise the capillary barrier concept to keep one (or more) of its layers near saturation under all climatic conditions. This creates a "blanket" of water over the reactive waste material, which reduces the ingress of atmospheric oxygen and subsequent production of acidic drainage.

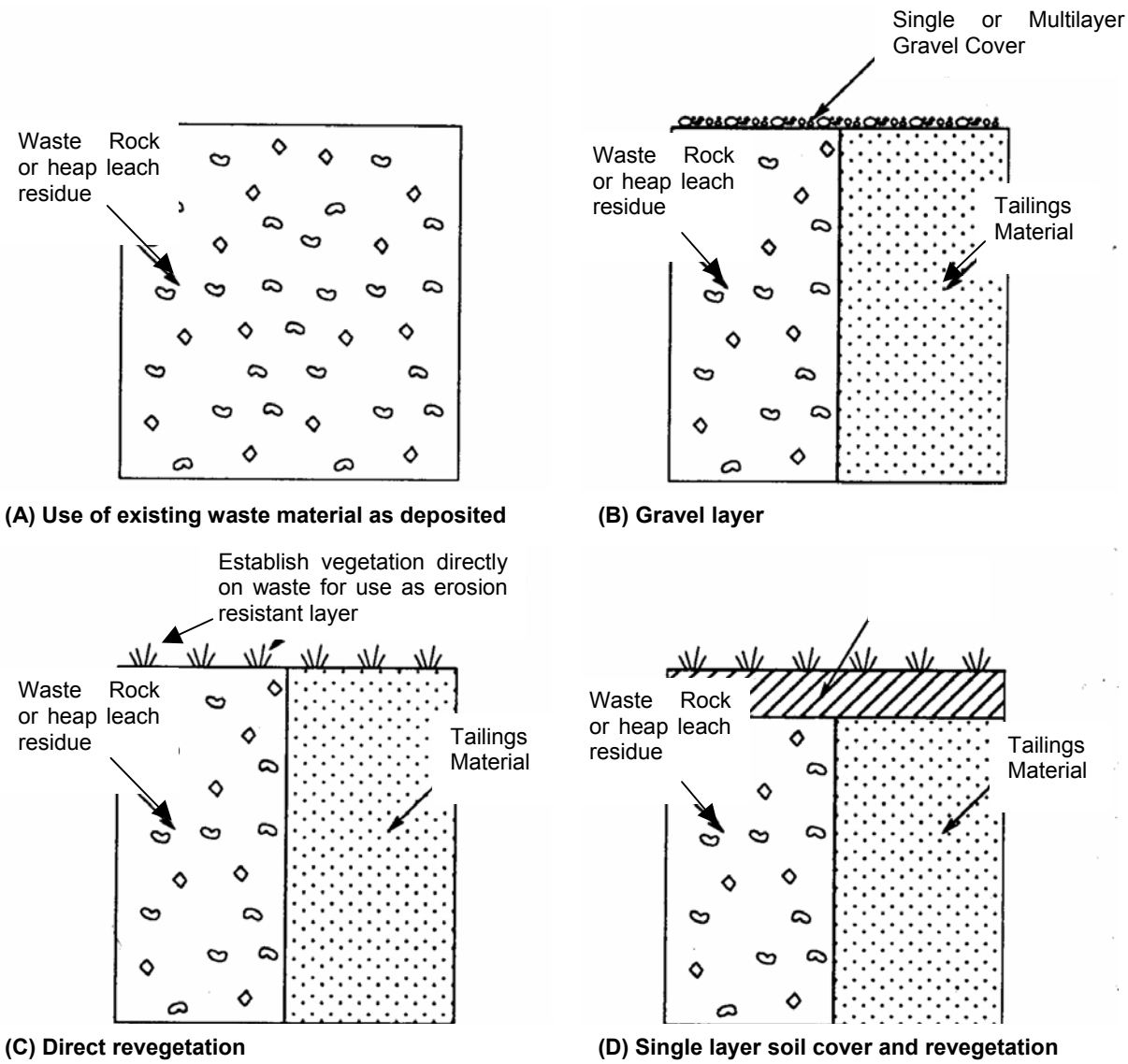


Figure 60: Simple dry covers as single layer systems [52].

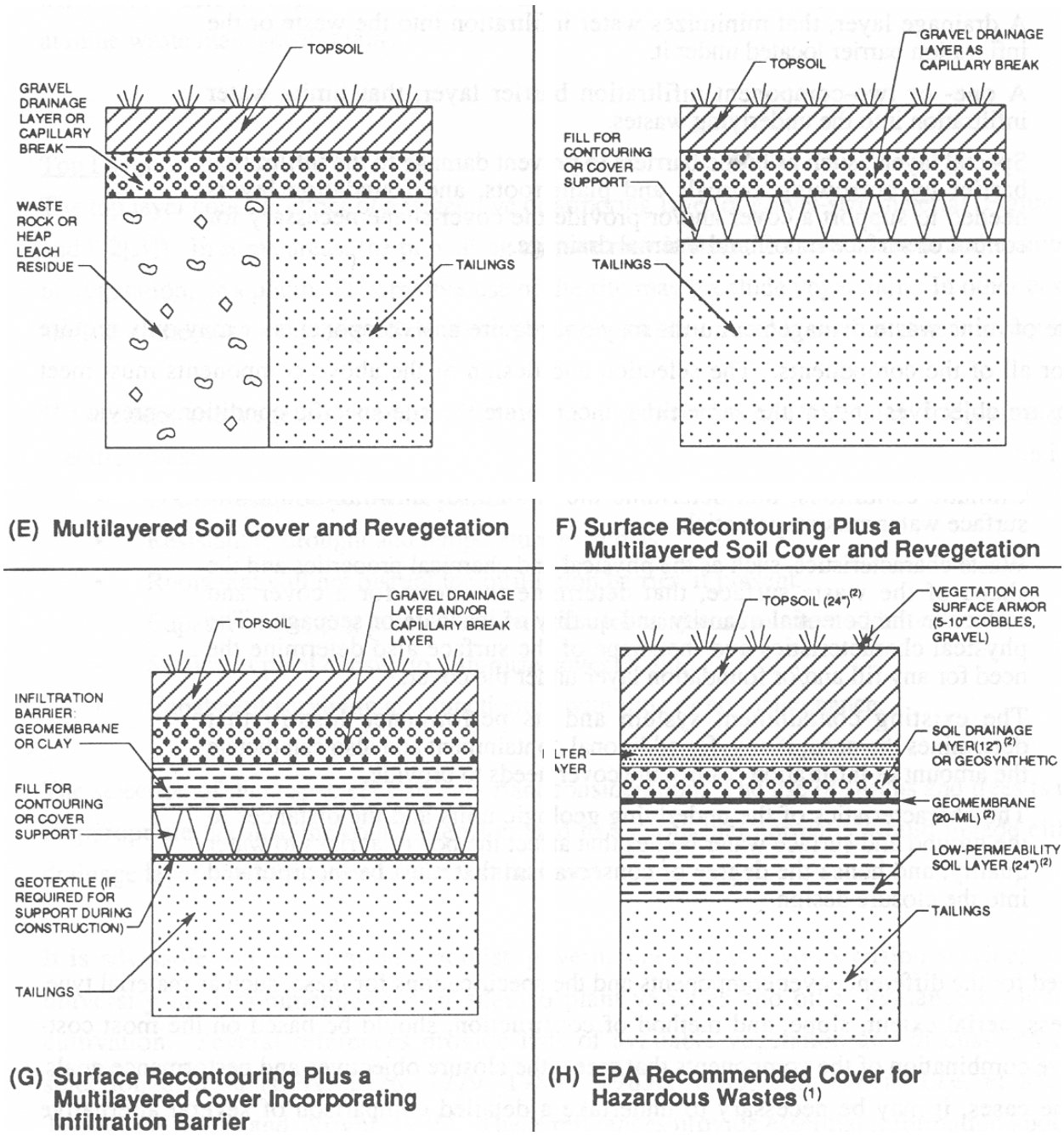


Figure 61: Complex multilayer dry cover systems [52].

For the covering of landfills and tailings material different regulations and rules exist in dependence on development in research and application. The EU-regulation (1999) gives the framework for all other EU-Countries. For Germany there are the technical instructions TA-Abfall (1991), TA-Siedlungsabfall (1993), the Thuringia Instructions TMUL (1994) and the landfill regulations DepV (2002) on the base of EU regulations (1999).

A dry cover system is subdivided into vegetation, surface layer, protective layer, biobarrier, drainage layer, seepage and infiltration barrier (Figure 62).

Dependence on the development of knowledge of the different components more or less exists. The design of a capping system will depend on available material, the water balance (climate, precipitation, infiltration, evaporation, evapotranspiration) and the long term behaviour of tailings material. The long-term behaviour is especially responsible for the arrangement of reinforcing geotextiles among the joint faces.

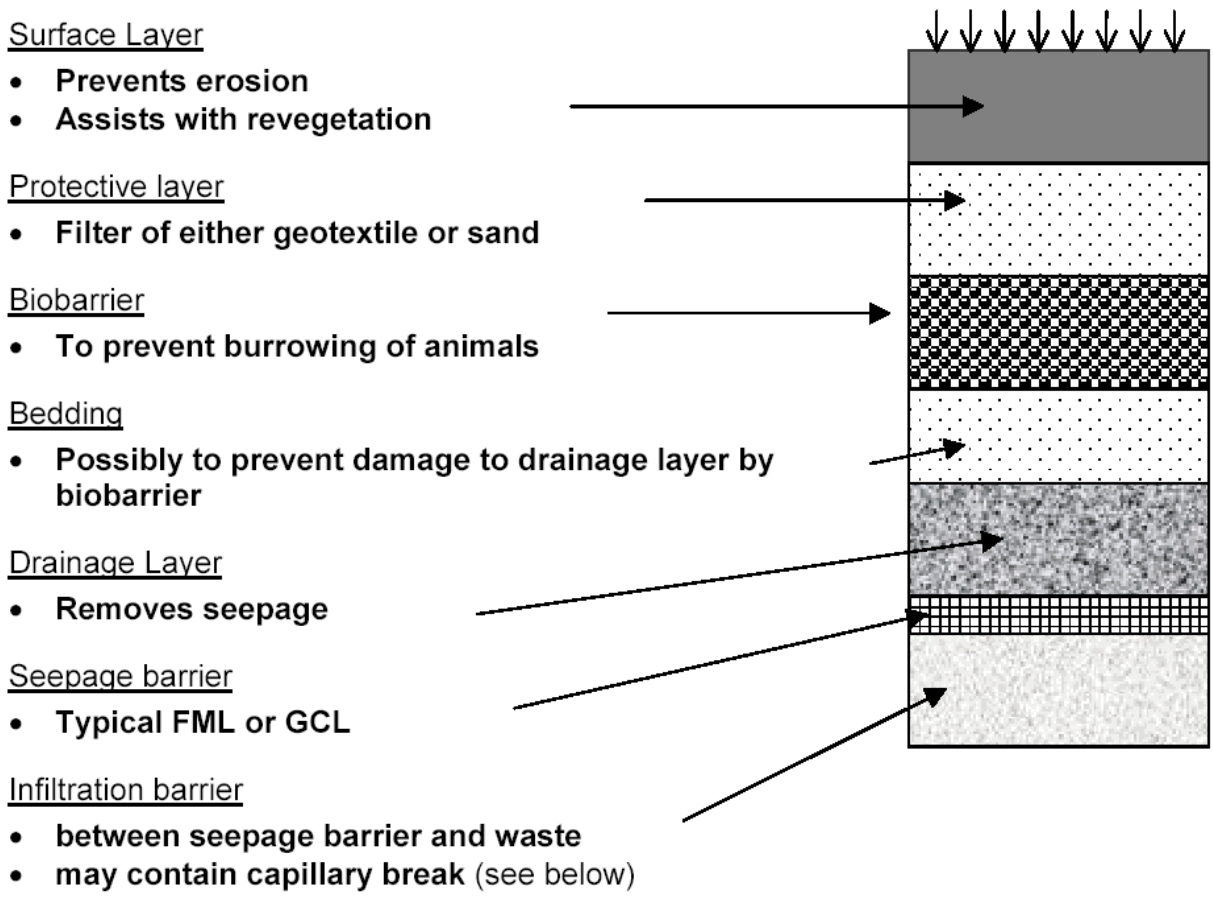


Figure 62: Principle components of dry cover-systems [112].

The different national and guideline regulations concerning landfill design induce certain dimensional and application profiles for each layer. Some of them are summarised in [112]. The theoretical background and some useful experience are presented in the guidelines E2-30 of the German Landfill Design guidelines [28]. E2-20 [28] describes how to calculate the balance of water in capping systems.

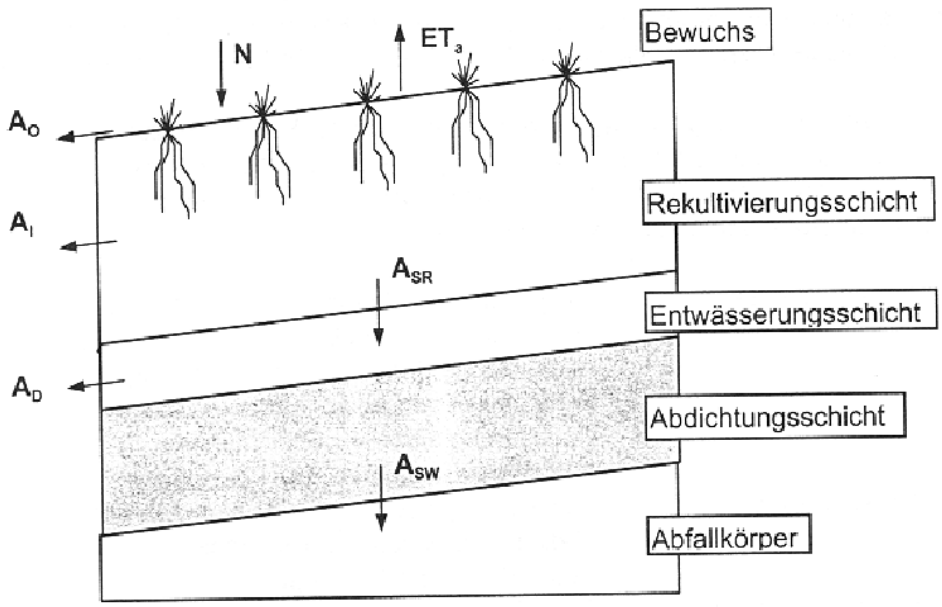


Figure 62: Cover systems based on GDA E 2-30 [28].

In Table 7 common dimensions and layer types for the different functions in dry cover systems are summarised.

All these regulations focus on landfill cover systems, reducing infiltration of precipitation and sealing against the emission of gas. We need special solutions for tailings impoundments and these should be optimised in accordance with the climatic conditions. The main problem in covering is the weakness and deformability of the soft soils at the tailings surface.

The installation of capping or covering systems depends on the stiffness of the surface layer of the tailings impoundment. The excess pore water and the desiccation of upper tailings layers are a gradual process, which leads to significant increasing of shear strength, reaching the requested minimal value of 5-10 kN/m². This is a basic assumption for the application of technical equipment on the tailings surface. As mentioned before, different systems constructed of various types of soils in composition with geotextiles are reputed. The mechanical properties of woven geotextiles and geocomposites are responsible for the applied technology of strengthening of tailings material on the surface and the installation of the interim layer.

Further technologies using high tensile woven polyester geotextiles enable installation of interim cover systems in tailings impoundment with zero cohesion [92]. The tailings can be capped completely. Sludge locks are installed on the peripheral stable soil to anchor the geotextiles. These transfer the applied tensile strength to the subsoil.

Table 7: Design guidelines for cover elements [52].

LAYER	PURPOSES OF LAYER	LAYER ALTERNATIVES	TYPICAL THICKNESS	GENERAL REQUIREMENTS(1)
TOP LAYER	Minimize Waste Dispersion by Surface Water or Wind Transport.	Granular In Situ Mine Waste	Variable	• Slopes can vary from a minimum of 1-1/2 percent to the angle of repose of the material. • Slopes and material should be stable and provide durable protection against erosion. • Surface contouring to prevent surface runoff concentration in local areas or ponding of water.
		Vegetation	Not Applicable	• Slopes can vary from a minimum of 1-1/2 percent to 50 percent. • Slopes and vegetation should be stable and provide durable protection against erosion. • Vegetation should be: - Persistent. - Drought resistant. - Adaptable to local conditions. - Shallow-rooted.
		Surface Armor	1/2- to 5 feet	• Slopes can vary from 1-1/2 percent to the angle of repose of the waste pile. • 1-inch nominal gravel up to boulders approximately 3 to 4 feet in diameter. • Size and thickness of armoring layer should be based on rainfall intensity and slope.
	Support Vegetation.	Soil	6 to 24 inches	• Slopes can vary from a minimum of 1-1/2 percent to 50 percent. • Required thickness will depend on the vegetation type, end use of reclaimed area, and suitability of the underlying mine waste to partially support vegetative growth.
DRAINAGE LAYER	Minimize Percolation and Damage to Infiltration Barrier. Prevent Upward Capillary Rise of Liquids From the Underlying Waste.	Sand or Gravel	12 to 24 inches	• Slopes range from 1-1/2 percent to a maximum controlled by stability considerations. • Adequate capacity to handle at least five times the anticipated infiltration rate through the layer above. • The layer should include a gravel toe drain or equivalent to direct drainage flows away from the waste management unit. • In some instances, it may be necessary to place a soil filter or geotextile over the drainage layer to prevent clogging by fines.
		Geotextile Geogrid Geonet	Variable (30 to 150 mils)	• Performance should be equivalent to the overlying sand or gravel layer.
INFILTRATION BARRIER LAYER	Minimize Percolation Into the Waste.	Geomembrane	20 to 60 mils	• Slopes range from 1-1/2 percent to a maximum controlled by stability considerations.
		Soil With a Low Hydraulic Conductivity	12 to 36 inches	• Hydraulic conductivity ranging from 10^{-5} cm/sec to 10^{-7} cm/sec depending on site-specific needs. • Should be located below the frost zone.
SPECIAL LAYER	Minimize Damage to Infiltration Barrier.	Biotic Barrier	12 to 24 inches	• Large materials, such as coarse gravel, cobbles, etc.
	Support Cover and Promote Drainage.	Foundation Layers	Minimum 24 inches and up to tens of feet, as required for control of drainage and contouring of surface.	• Frequently can be constructed from mine waste such as centrifuged coarse tailings fractions, spent ore, or waste rock. • These layers may require compaction to assure adequate support of overlying cover layers.

Figure 63: Installation of geotextiles for improving the impoundment stability infront of the installation of cover systems.

4.5.4. Wet Covers

When stored under water, unoxidised sulphidic mine wastes are largely chemically unreactive. The use of water as a cover material has a similar objective to a saturated soil cover, in that it reduces the availability of one of the principal reactants, oxygen. The maximum concentration of dissolved oxygen in natural water is approximately 25,000 times lower than that found in the atmosphere. Once the available oxygen in water is consumed, the rate of reaction is reduced because its rate of replacement is relatively slow. The resultant diminished availability of oxygen is the single most effective inhibitor to sulphide oxidation.

Water covers are more readily achieved in temperate climates. Other methods to ensure saturation may be required in drier climates, for example, establishing a permanent wetland on the tailings impoundment surfaces, or designing a complex layered cover to trap precipitation on the tailings surface and inhibit evaporation. While the use of natural or artificial lakes as repositories for mine wastes may compromise other beneficial uses of these water bodies, in some instances it may be the best available option. There are examples of mine sites in Canada, Sweden and Germany where lake environments are being used for tailings and waste

rock disposal. Details of rehabilitating a mine pit by converting it to an aquatic habitat and potential water resource are provided in [46].

As a long term management strategy, subaqueous impoundment of sulphidic wastes is attractive because lake sediments tend to be a stable environment for sulphides. In addition to the low concentration of available oxygen, sediments have a natural tendency to become chemically reducing due to high organic matter levels and biological activity. Acid generating wastes, disposed of underground as backfill in mined-out workings, can be flooded at the end of mine life thus minimising long term sulphide oxidation rates. Nevertheless as a result of water waves and water circulation, the oxidation process can take place.

But the method of wet covering implies possible risks like a high phreatic level and wide range of seepage water giving all in all a high hydraulic impact to retaining structures. Furthermore a minimum water level must be guaranteed.

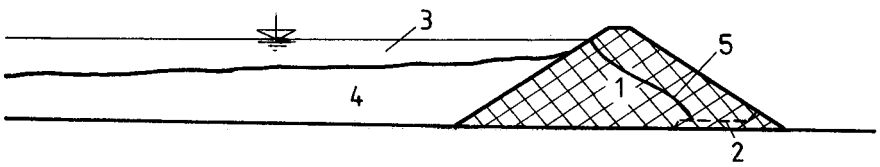


Figure 64: Tailings always remain under water [53].

5 Strengthening of tailings impoundment by less conventional methods

5.1 Introduction

Over the last 15-25 years, tailings ponds have ceased to be considered of secondary geo-/ hydro-technical importance, as they used to be considered previously, due to their role as waste deposits. This change of attitude has many causes, but especially their considerable increase in height, in volume of material deposited, in occupied land surface, and in the dangers of possible failure or of environment pollution effects.

There are many options for managing tailings and waste-rock. The most common methods are [56]:

- dry-stacking of thickened tailings slurries
- dumping of more or less dry tailings or waste-rock onto heaps or hill sides
- backfilling of tailings or waste-rock into underground mines or open pits or their use for the construction of tailings dams
- discarding of tailings into surface water (e.g. sea, lake, river) or groundwater
- application as a product in land use, e.g. as aggregates, or for restoration
- discarding of slurried tailings into ponds.

Waste-rock is either managed on heaps or is sometimes dumped on existing hill sides. The ways in which these different techniques are applied will be discussed in this section.

5.2 Characteristics of materials in tailings and waste-rock management facilities

5.2.1. Shear strength

The shear strength is the most important characteristic of any tailings or waste-rock, in the design of a heap or dam. Normally the appropriate shear strength parameters necessary to carry out a stability analysis are those related to the effective stress, i.e. the effective cohesion and the effective angle of shearing resistance. Comparatively small variations in the shear strength parameters used may have a significant impact on the safety factor. Therefore strength tests are carried out on a reasonable number of samples.

5.2.2. Other Characteristics

Other important characteristics relevant for the stability of a facility are [56]:

- particle size distribution: as this influences shear strength
- density
- plasticity
- moisture content
- permeability, according to their coefficient of permeability k (in cm/s) tailings and waste rock are classified in three groups:
  - permeable: $k > 10^{-3}$
  - semi-permeable: $10^{-3} > k > 10^{-6}$
  - impermeable: $k < 10^{-6}$
  - consolidation: the amount and rate of settlement of tailings or waste-rock under load are related to the consolidation characteristics of the soil.

Tailings dams are surface structures in which slurried tailings are managed. This type of Tailings Management Facility (TMF) is typically used for tailings from wet processing. Ponds normally consist of 20 - 40% solids by weight, but levels from 5 - 50% solids have been known.

The basic arrangements of tailings dams may be classified as:

- existing pit
- valley site
- off-valley site
- on flat land.

For each tailings impoundment, several activities need to be considered, including:

- tailings delivery from the mineral processing plant to the tailings dam,
- the formation of dams to confine the tailings,
- diversion systems for natural run-off around or through the dam,
- deposition of the tailings within the dam,
- evacuation of excess free water,
- protection of the surrounding area from environmental impacts,
- instrumentation and monitoring systems to enable surveillance of the dam,
- long-term aspects (i.e. closure and after-care).

Some of these activities will be discussed in the following sections. Also some aspects of seepage flow and design flood considerations will be introduced. These two aspects have an impact on several of the activities listed above.

5.3 Confining dams

The construction materials and methods used in forming the dam vary widely to accommodate the particular needs of the selected site, the availability of materials and the financial and operating policies of the entire operation.

Typically, dams are subdivided into three parts [56]:

1. an upstream section which is capable of retaining the tailings without excessive penetration/erosion by the tailings themselves (e.g. compacted sand);

2. a middle section, or core, which provides a passage for seepage water through the structure in a controlled manner and which will not break down or become blocked by fine material (e.g. rock or crushed filter stone) and;

3. a downstream section which provides toe strength and stability and which will remain "dry" under all circumstances (e.g. sand compacted to a high density). In some circumstances, it may be necessary to incorporate artificial membranes (filter cloths) between the main sections of the structure where there is a risk of high seepage and the movement of fine material.

The dam types may be classified as follows:

- non-permeable (water-retention type) dams;
- conventional dam;
- staged conventional dam;
- staged dam with upstream low permeability zone;
- permeable dams
    - dam with tailings low permeability core;
    - dams with tailings in structural zone;
    - upstream construction using beach or paddock.

These types will be briefly discussed below.

Note that the term beach used in conjunction with the management of slurried tailings in a pond means the area of tailings resulting from the settled solid fraction of tailings slurry, in a pond not completely covered by free water, between the edge of free water and the crest of the dam.

The purpose of a beach is to establish an area of "dry" tailings against the upstream face of retaining dams, for two important considerations:

1. to prevent water from reaching the crest of the dam where it could cause erosion of the inside face, or more seriously, lead to excessive leakage through the dam with the subsequent risk of "piping" and possible damage/collapse of the structure;

2. to allow "natural" separation of the coarser and finer particles of the tailings. Where tailings are discharged into a dam by suspension in water (and most are) the larger sized particles tend to settle out more quickly. As these "dry" out and consolidate, densities will generally increase over time, thereby adding to the overall stability of the structure as a whole.

5.3.1. Conventional dam

This type of dam is completely built before tailings are discharged at the site. Hence, tailings cannot be used to build the dam. Conventional dams are constructed where the confinement is to be effected for both tailings and free water during the whole period, from the start of tailings management to the end of the particular site selected [56].

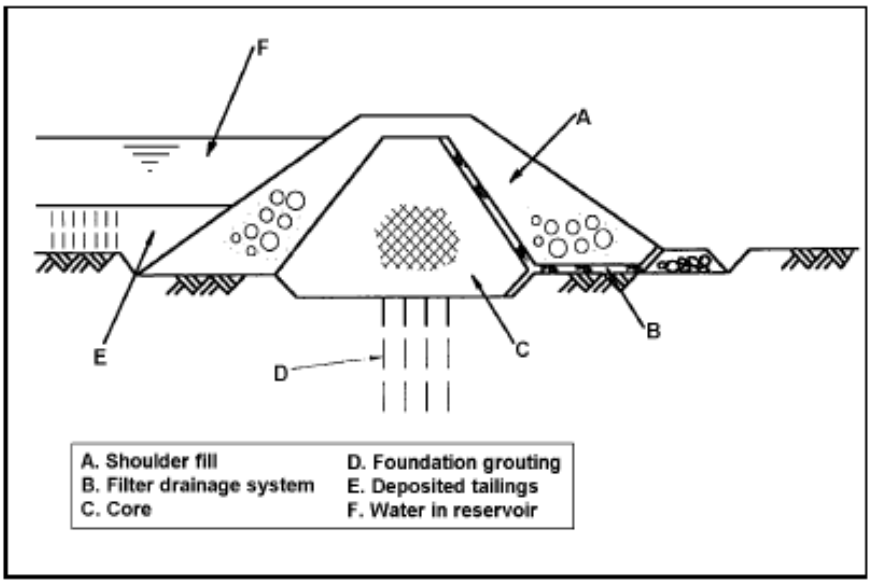


Figure 65: Conventional dam [54].

The purpose of the shoulder fill indicated in Figure 65 is to increase the overall dam strength, but also to protect the core from erosion (wind and water) and from wave action from the free water.

A conventional central core section is illustrated in Figure 65 but the range of options is varied and similar to that for dams designed to confine water alone. In general though, the dam must be capable of:

- controlling the passage of water;
- supporting the loads imposed by the tailings and water in the impoundment;
- transmitting the seepage water effectively and without the passage of solids (filtration system).

5.3.2. Staged conventional dam

This is similar to a conventional dam but has a lower initial capital cost by staging the construction so that the costs are spread more evenly over the period of deposition (Figure 66).

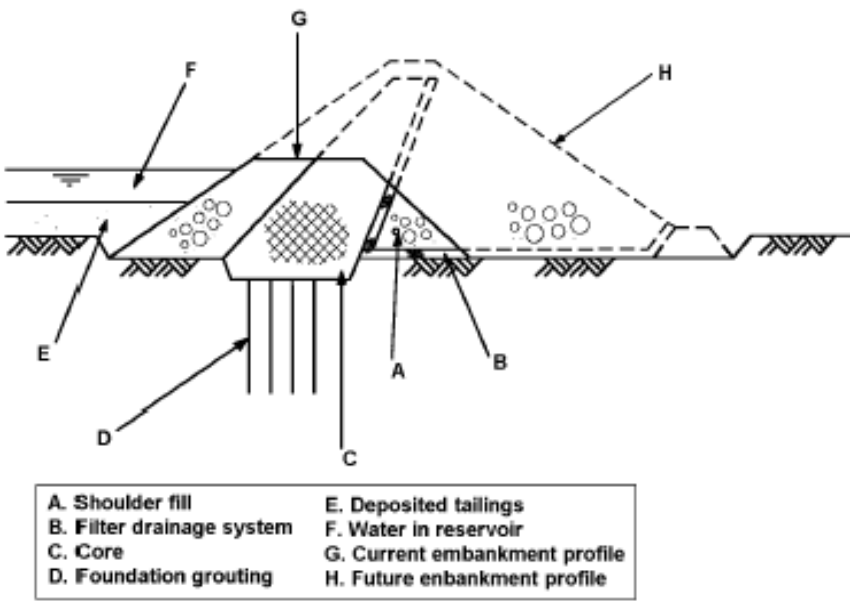


Figure 66: Staged conventional dam [54].

5.3.3. Staged dam with upstream core

If the deposited tailings lie close to or above the level of the free water in the impoundment, the low permeability core zone of the dam may be located on its upstream face (Figure 67). This is possible because the core is protected against erosion and wave action by the tailings [56].

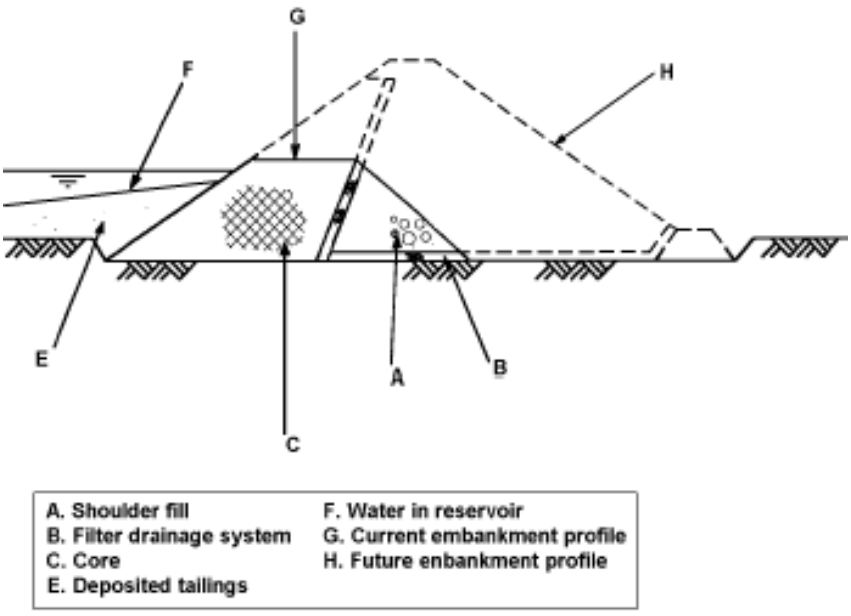


Figure 67: Staged dam with upstream low permeability zone [54].

5.3.4. Dam with tailings low permeability core zone

Where all or part of the tailings deposition into the pond occurs from the dam, a beach of tailings may be formed (Figure 68). It is then possible for the tailings beach alone to provide the less permeable zone of the system [56].

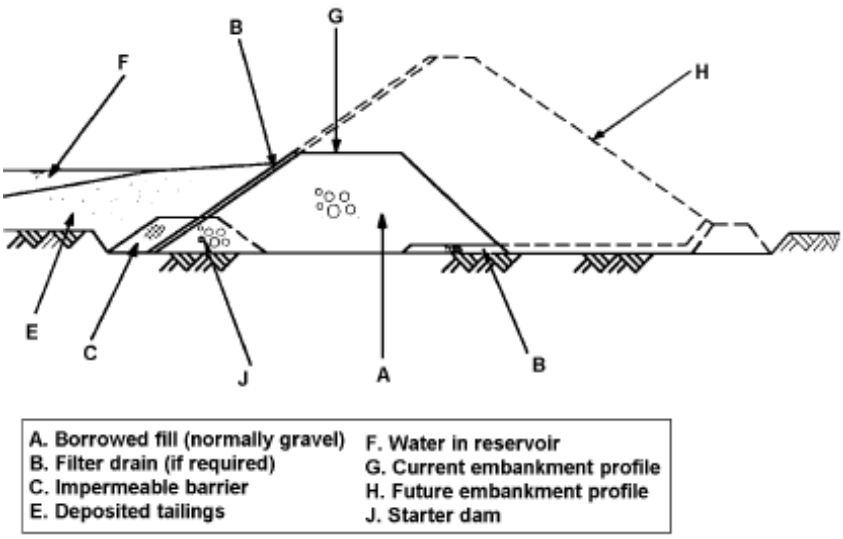


Figure 68: Dam with tailings low permeability core zone [54].

This arrangement is only possible where the inflow of water will not allow the impoundment water level to rise above the uppermost level of the beach and therefore against the more

pervious dam material. Therefore, continuous monitoring is required for this kind of arrangement. For this arrangement it is necessary to build a low-permeablily barrier (C) into the starter dam, until the beach has developed far enough away from the dam itself.

5.4 Seepage flow

A tailings dam will influence the original groundwater flow pattern by introducing a hydraulic gradient (difference in hydraulic head between two points divided by the travel distance between the points). Figure 69 shows schematic seepage flow patterns for original groundwater flow conditions and for the following basic dam types:

- existing pit;
- valley site;
- off-valley site;
- on flat land.

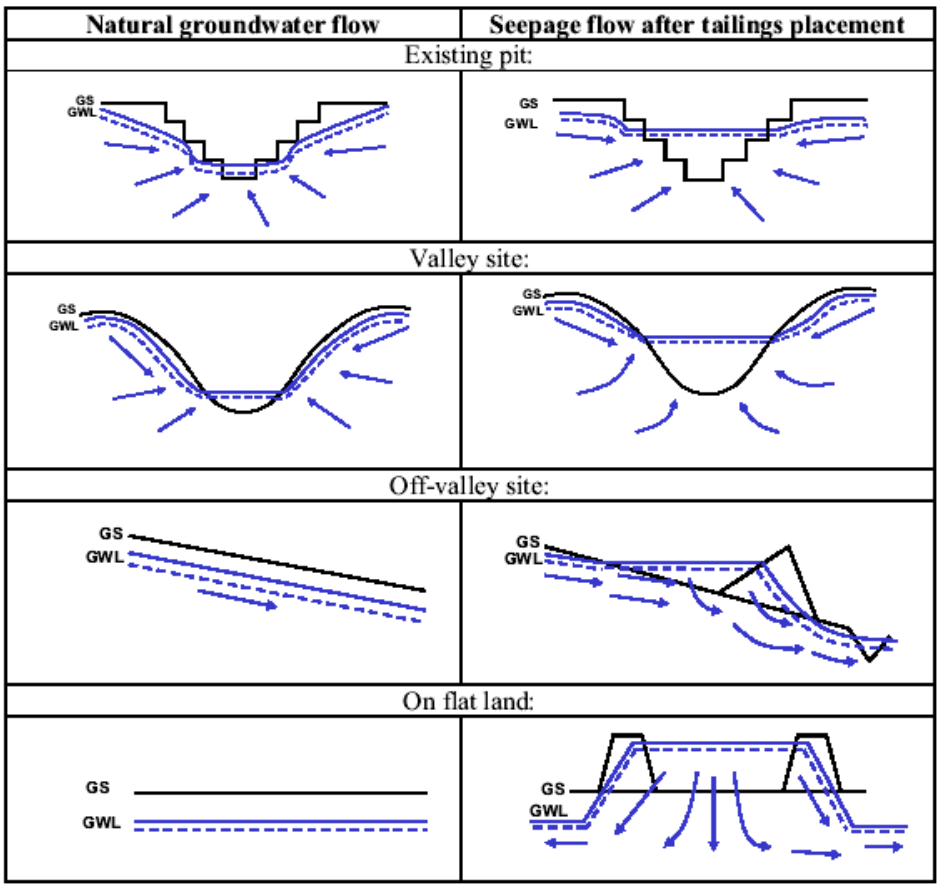


Figure 69: Simplified seepage flow scenarios for different types of tailings ponds [56].

It should be noted that these are simplified schematic two-dimensional drawings. In the real world the actual flow pattern will be influenced by factors such as:

- dam properties;
- water level in the dam;
- permeability of the underlying formations;
- ground layering;
- original groundwater flow regime.

5.5 Dam drainage works

5.5.1. Drainage mattresses at the dam base

It is important that controlled seepage occurs through the dam to assure stability by lowering the pore pressure within its structure. However, it is essential that this seepage is well controlled and managed both for its day to day environmental performance, as well as from an accident prevention point of view.

Seepage control is used in the management of any dam construction. By monitoring the normal seepage flow through the dam, in combination with a good understanding of surrounding processes (meteorology, water level in pond etc.), an early indication can be obtained of potential problems within the dam. Increased flow, in combination with suspended particles in the seepage, could mean that piping is starting to occur. Decreased flow could imply clogging of the drainage/filter.

Due to the prevailing hydraulic gradient (hydraulic pressure difference) between the pond and its surroundings, seepage occurs not only through the dam but also under the dam and in some cases also through natural ground that serves to confine the tailings. Differences in the hydrogeological settings between sites make it necessary to conduct site-specific evaluations. Depending on the outcome of these hydrogeological investigations and the necessity to collect the seepage, there are various prevention and collection options available. In many cases, a combination of available measures is preferred.

If a dam is built without any internal drainage system, the conditions of Figure 70 will develop. In practice the emergence of seepage from the outer slope and saturation of the outer toe are to be avoided, as this may lead to instability unless the slope is very flat.

Permeable dams are based on the principle that seepage through the dam should be drawn down well below the toe of the outer slope. This can be achieved by an internal drainage system, with the drainage zone being located in the inner section of the dam.

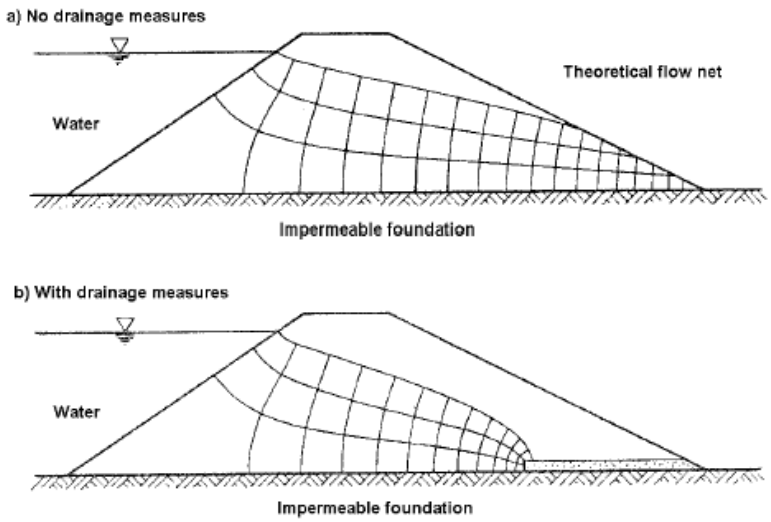


Figure 70: Dam without and with drainage system [4].

Care has to be taken, so that the drainage system, sometimes also referred to as the filter system, does not get plugged with tailings material. Consideration has to be given to the groundwater conditions. In some cases it may be necessary to design a drainage system which will deal with both the groundwater and the pond drainage. An example of a permeable dam with a drainage system can be seen in Figure 71.

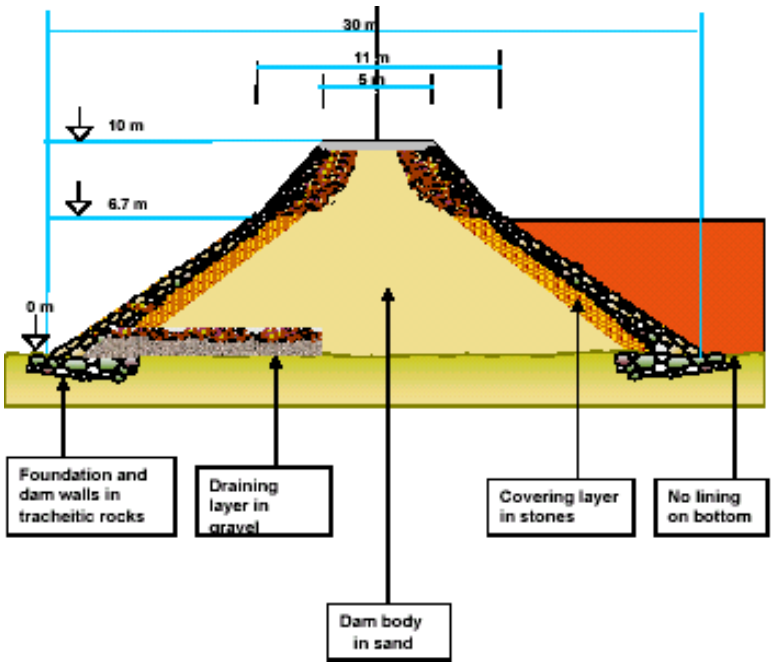


Figure 71: Cross-section of tailings dam [56].

At the Kernick mica dam, sand tailings and waste-rock have been used to construct a dam in specific zones separated by transition layers. The waste-rock, evenly graded between 50 mm and 750 mm in size, forms a central core for the capture and drainage of seepage through the structure. The sand tailings, containing no material larger than 150 mm but typically less than 25 mm grain size, forms both the downstream and upstream parts of the main dam [56].

The transition layer, consisting of clean, crushed rock typically between 75 mm and 125 mm, forms a filter layer between the sand tailings and the waste-rock core.

It should be noted that non-permeable dams also have systems similar to the drainage system shown in the figure above. In this case the filter has the purpose of keeping seepage flow through the core from eroding the core and the outer slope of the dam. A typical filter for this type of dam can be seen in Figure 72.

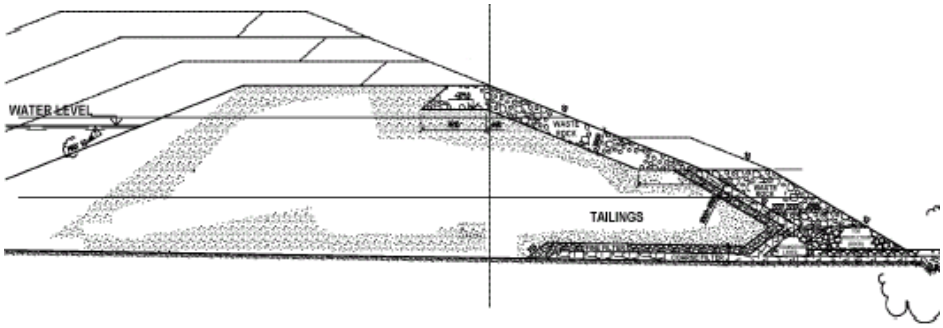


Figure 72: Drainage system [56].

At the base of waste dams, in order to increase their resistance, mineral draining cushions are placed. Such cushions are formed from an alternation of gravel, rockfill and sand, with their particle distribution in accordance with filtration criteria, as well as a collecting drain.

The draining cushion placed on the embankment slope advances from the toe, extending as the embankment is raised. This method presents the advantage of drainage intensification, but chiefly of depression curve maintenance at a reasonable distance from the dam slope.

The mineral aggregates from the cushion have two or three layers, with an increasing granulometry in the direction of the water flow (reverse filter). The granular filters are designed on the basis of rules fulfilling two requirements, represented by:

- a condition of protection or stability, which defines the requirement that the filter must have a size small enough to prevent fines passing from the protected ground;
- a condition of hydraulic efficiency, which requires that the filter have sufficient permeability to allow water to pass, without a pressure increase, which could occur even when the hydraulic gradient is low.

In the case of cohesive materials, for which it is accepted that instability phenomena can occur on a local plane, along preferential flow paths, to the condition of protection there is added a requirement that the filter must not present local discontinuities.

Factors which could facilitate the appearance of such discontinuities are segregation of the filter material and the possibility of fissure propagation in it. Both aspects are related to the fact that in order to fulfil the condition of protection, according to customary requirements, filters used to have a wide granulometry and a high content of fine material. In consequence, such filters have been liable to segregation, and need cohesive properties able to prevent the formation of a transverse fissure.

The inadequate behaviour of some filter protections applied to clayey materials drew attention to the fact that for those cases, and especially for the situation of flows on preferential paths, filter sizing in accordance with the customary criteria is not satisfactory. It is now unanimously accepted that Terzaghi criteria validity is limited to the granular materials.

The mineral reverse filters gave and will give good results if they are well designed and carried out. Geotextiles also now offer an alternative with many advantages. For cohesive-dispersive or non-dispersive materials, geo-textiles can represent, by themselves or in association with a granular filter, the only solution which assures continuity and resistance of the filter element, controls the formation of fissures, and is able to close fissures.

Geo-synthetic drainage cushions are manufactured from geo-networks (consisting generally of polyethylene with the addition of about 2% smoke black and 0.25-0.75% additives such as antioxidants and lubricants), used separately or in association with geo-textiles (with a drainage core consisting of shaped extruded polymeric materials). The geo-composites obtained in this way accomplish the jobs of filtration, separation and drainage, all much improved by the presence of the geo-textiles).

The drainage capacity of geo-textiles with a shaped core is in principle independent of the pressure applied, as the core profile is considered non-deforming under the load the geo-textiles have to bear in situ; the materials are sized accordingly. However, as the geo-textile composite with a filter matting can become deformed under load, a reduction in its drainage capacity is possible. This can be experimentally determined, or is directly specified by the producer as a material characteristic. Also, for the compound geo-textiles, a reduction of the drainage capacity is not taken into account, as by design the draining element works under the protection of an efficient filter. Figure 73 shows different solutions to decrease the negative effects of water infiltration from the dam base.

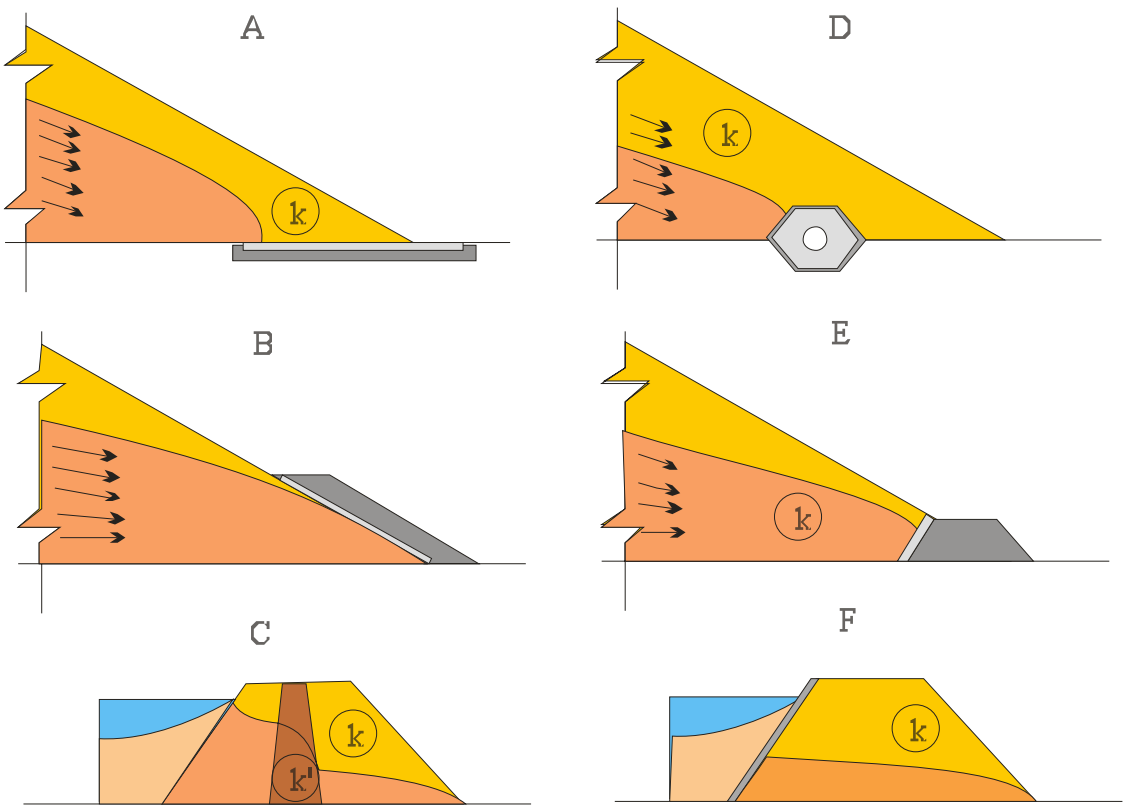


Figure 73: Different solutions to decrease the infiltration negative effects a. drainage mat, b. burden on the down stream slope (slope drainage), c. core sealing, d. tube drainage, e. drainage bench, f. sealing screen [33].

5.5.2. Multi-storied drainage

In the case of some ponds carried out with an impermeable or low permeability starter dam, but also when the point of emergence of the depression curve is seen to rise to undesirable levels on the dam slope, the installation of continuous or multi-level drains during deposition can be sufficient.

In order to increase the stability of the tailings pond, drainage works on several levels may be necessary, employing inclined mineral drains of about 1 m thickness (crushed stone, gravel and sand – with a particle distribution in accordance with filtration criteria) together with collecting pipes.

In recent years, geotextiles have been used alone or in association with suitable minerals, for such multi-level drains. Such geotextiles are usually woven (with a three-dimensional structure consolidated by inter-weaving, chemically or by sewing) or they may be compound geotextiles resulting from the combination of a filterable geotextile with draining band material, such as the Filtram or Enkadrain type.

The functional requirements which have to be fulfilled by geo-textiles for a draining role are the following:

- drainage capacity in the conditions under which they work, determined by the ground-water flow and overburden load;
- filtering efficiency, for whatever specific filtration role is to be fulfilled, in order to facilitate the drainage role. (This is an additional role of the same material in the case of classic non-woven geo-textiles, but an independent role in the case of the filter covering layer of compound geo-textiles.)

For fulfilment of their filtering role, the geo-textiles have to assure the filterable protection of a granular medium or form a filterable barrier in a liquid flow containing particles in suspension). In tailing ponds, the water flow is unidirectional.

In comparison with classic filters from granular material, geo-textile filters present a number of advantages due to their special filtering efficiency (thanks to the high permeability and porosity of geotextile materials within a reduced diameter of flow), the continuity of the filter layer and its resistance to mechanical stress, the constant and controllable quality of the material, the low total power consumption, the possibility of accomplish installation works in a more advantageous technical and technological manner, the simpleness and lightness of such installation, the possibility of using different geo-textiles on a job in which several ground types appear (whereas the utilization of some mineral filters only within certain zones is unworkable), and comparable cost with the classic solutions.

In many situations, one or more of the advantages specified above may be essential to the optimum solving of the design problem. Thus, in the case of filters applied on cohesive ground, where one encounters flow on preferential paths, the cohesion and resistance to mechanical stress of geotextile filters represent very important advantages. Thanks to those characteristics, they can perfectly assure filter continuity and stability in the eventuality of irregular subsidence or the development of high local gradients.

Protection filters have a role in assuring the hydrodynamic stability of the granular medium they protect. However, such a filter must not be considered an inert barrier, simply stopping the particles drawn by the water flow. Embedded in the earth, it actually represents a catalytic element which, in an evolutionary process, helps to form a natural filter (auto-filter) at the earth/geotextile interface.

In that context, it is accepted that a protection filter must not stop all particles drawn by water, but has to selectively assure their passing through. As a result, a part of the fine fraction can be

eliminated from the contact area, leading to a reduction in the discontinuity between the earth and the natural filter.

In the case of geo-textiles, their material thickness assures an advantage for non-woven products in comparison with the woven ones. In addition, the non-woven geo-textiles, thanks to their spatial structure and lines of flow, achieve their restrictive effect against a wider granulometric domain (i.e. a wider range of particle sizes). As a result, although woven geo-textiles were the first to be used as filters, non-woven geo-textiles stand out for such applications.

The development and evolution of the filtration process depend on many factors relating to:

- soils characteristics and structure (granulometry, porosity, degree of compaction or cohesion);
- filter medium characteristics and structure (porosity, permeability, capacity to retain solid flow);
- nature of ground and geo-textiles (mineralogical and chemical composition of the ground and the type of the polymer from which the geo-textile is manufactured);
- the stresses applied (loading, flow gradient and reversibility of the stress);
- installation standard (in particular, attainment of necessary contact between ground and filter).

The functional requirements which geotextile filters have to fulfil (as for filters from granular material) are expressed by the two conditions:

- condition of protection or retention
- condition of hydraulic efficiency or permeability

Granular filters are defined by criteria which establish correlations between grain diameter, pore size and granular medium permeability.

In the case of geotextiles, for which the relationships between fibre diameter and pore diameter have not yet been established with any certainty, the existing type correlations for granular media cannot be applied.

In consequence, we need to look to other parameters for the determination of some criteria to define the two conditions: for the condition of protection, we look at the capacity of the geotextile to retain solid particles, as expressed by its filtration diameter; while for the hydraulic efficiency, we look at its permeability characteristics.

In the case of the drainage function, the capacity of the geotextile to constitute a good capillary barrier or break is crucial. Weather conditions in many European countries, sometimes

has long periods of severe freezing, mean that many buildings and especially much communication infrastructure undergo a lifting action by water freezing from the capillary fringes. The utilization of a drainage horizon formed from geo-textiles can be beneficial, as it breaks the continuity of the capillary tubes in the earth. In addition, it has to be mentioned that the product itself is hydrophobic, due to the polymers from which it is made: a fact which supports its capillary break performance.

By comparison, with a mineral filter made from sand, water is attracted to grains by other forces, too, so we have a hydrophilic material, which does not assure a break in the capillary fringes. This difference of behaviour favours the use of geotextiles as capillary barriers.

5.5.3. Drainage adapted to anisotropic tailings

Due to the conditions of sedimentation and hydraulic separation, a tailings dam constituted from sediments from the tailings themselves, can have an accentuated anisotropy, either in the form of a completely different permeability vertically and horizontally (despite apparent uniform sedimentation), or due to the existence of a sequence of layers with completely different permeability.

Improvement of the drainage conditions in such cases may be achieved either during the raising of the dam, or by interventions on the surface of the deposit.

In the first case, as the body of the dam is lifted, cross layers will be incorporated from granular material with a permeability 1 - 2 orders greater than that of the body of the dam, or from drainage geo-textiles.

In the second case, “short-circuiting” of the sandwiched layers with vertical tubes should be tried. Installation of such tubes is performed by percussive rotary drilling, pile driving/hammering, and rod vibration. Some wick type drains are formed from geo-textiles, using hydraulic drilling equipment, and discharge into a layer of drainage geotextile, situated at the dam surface, with downhill flow.

5.6 Impoundment sealing works

5.6.1. Cementation and strengthening of fines by injection

NaOH Injection

Where it is desired to increase the stability of a dam constructed from dusty-clayey material, an intense basic solution can be injected, for example NaOH in solution (5-10 N), to achieve the slight consolidation of material inaccessible to other injection fluids, because of their lesser

permeability and high humidity. However, the handling difficulties, pollution risk to the surrounding area and possible chemical attack of underground construction elements can all be drawbacks.

The cementation effect performed by intense basic matters within fine earths results from interactions at the level of the adsorption complex, consisting of ion exchange, the decomposition of alumina silicates from the earth under action from the basic matter, and the forming of new compounds, including some having a strong cementitious effect.

Another problem is that with the passage of time, or because of imperfections in the protective cover of the tailings pond, there can develop an intense phenomena of internal erosion of the cemented curtain wall. A gradual decrease of efficiency of the structure is observed (i.e. a decrease of modulus of deformability of the injected rock and increase in permeability of the barrier) as a result of lime leaching from the cement stone:

$$Ca(HCO_3)_2 + Ca(OH)_2 \text{ turns into } 2\ CaCO_3 + 2H_2O$$

Subsequently, the water depleted of bicarbonates leaches less lime from cemented stone and partly carries it outside the construction, and partly into fissures. This calcium oxide rich flow meets in the fissures the main water flow bearing bicarbonates, which results in calcium carbonates forming and settling, while the rest of the calcium oxide is removed beyond the fissures. Because of the possible aggressivity of tailings ponds waters, there is a requirement for multi-layer impermeable geo-synthetic coverings able to resist water aggressivity variations in tailings.

Aluminous cement injection

This method could remove some of the immediate and potential disadvantages presented by thousands of existing tailings ponds and heaps, as it would allow the transformation of tailings in a high density agglomerate (2000 - 3000 kg/mc) with a mechanical resistance varying between 5 and 30 MPa. This would be achieved by the injection of aluminous cement milk by means of a simplex or duplex sludge pump (of mineral oil type) across the whole tailings pond surface, and as far as the back of the dam which delimits it. In this first stage, the fluid waste would be turned into a 20-50 MPa “concrete” [75].

This method could be applied either by slope injection as a partial solidification if the volume of deposited tailings are high, or as a total solidification if the tailings volume is small.

Ash and waste dumps from power plants may be similarly treated by impregnation with cement milk to a depth of about 2 m, so that a sarcophagus is created able to resist the weight of a tractor or a truck.

The over-rising dams (which follow the starter dams) would then always be constructed from the tailings hydro-mass originating from flotation, mixed with aluminous cement milk, transported and settled by means of a Putzmeister plant.

The advantages of this approach have been put as follows [75]:

- stabilization of tailings ponds by transforming fluid waste into a solid conglomerate.
- approach can be applied to all tailings ponds however old they might be;
- in comparison with other strengthening methods, is less expensive and the results are achieved sooner;
- consolidation can be carried out without interrupting use of the tailings pond;
- after solidification, the tailings pond becomes a structure with well defined mechanical characteristics, able to bear built structures, recreation and sports grounds.

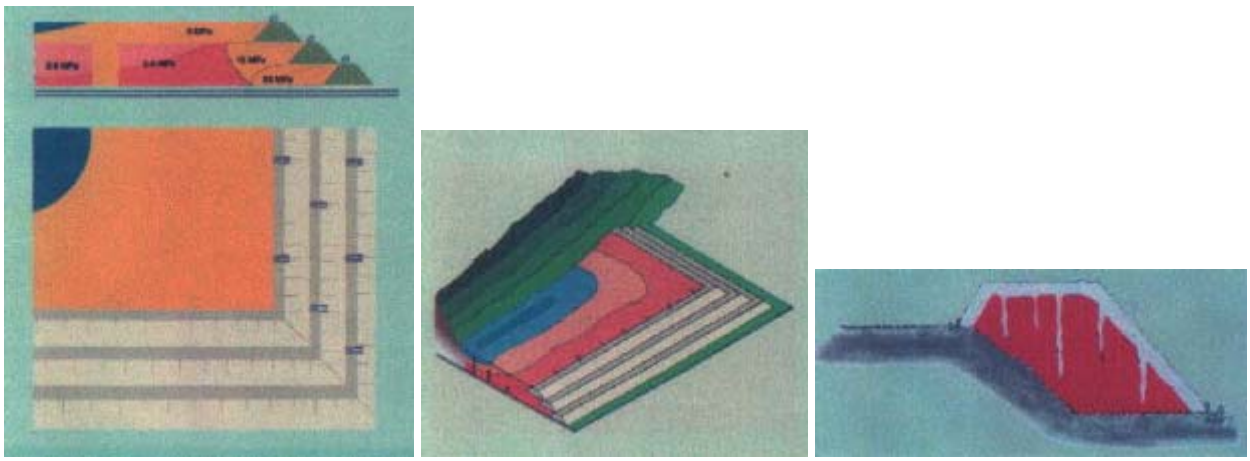


Figure 74: Consolidation of tailings ponds by cement injection [75].

5.6.2. Sealing using bentonite

Bentonite is the commercial name for clays that are largely made up of the mineral montmorillonite. When mixed with water, bentonite (especially of the sodium montmorillonite type) is highly expansive and can absorb many times its own weight in water. This swelling action is helpful in sealing pores and cracks in leaking earthen containments.

Sodium bentonite is available in bulk in its natural state or it can be processed into powdered or granular forms.

Bentonite is non-toxic to livestock and fish. To prevent leaking in farm dams or tanks, a number of techniques can be used to place the bentonite. These methods include:

- Mixed blanket
- Pure blanket
- Dispersed blanket
- Injection/slurry trenching.

Of these methods, the dispersed blanket technique is the only one suitable for treating dams which contain water.

The mixed blanket method

This technique uses powdered bentonite and is suitable in soils with a loose and friable nature e.g. sandy loams. It is not suitable in heavy soils or soils containing clods of moist heavy clay, because a consistent mix with the bentonite cannot be achieved. The procedure is [44]:

- Level out any irregularities in the area to be sealed.
- Remove weeds, rocks and stumps.
- Loosen the surface soil to a depth of 100 mm using a disc cultivator, rotary hoe or similar implement. Work the soil up to a reasonably fine condition.
- Peg out the area in 2.25 m by 2.25 m squares.
- Place 40 kg of bentonite in each square and spread evenly by hand raking. This procedure will ensure an even application rate of 8 kg of bentonite per square meter of surface area.
- Thoroughly mix bentonite into the soil until it is evenly dispersed through the loosened layer. This will be apparent when the soil takes on a uniform grey colour.
- For small areas mixing can be done by hand. For larger areas a disc cultivator or a rotary hoe is preferable.
- Compact the mixture with a heavy roller. Rolling will be easier and more successful if the soil is moistened slightly. A flat or rubber tyred roller is suitable but a sheeps-foot roller will do a better job.

If a sheeps-foot roller is used, the feet of the roller should be shorter than the thickness of the compaction layer.

A reduction in seepage of about 90% or better can be achieved using this technique. However, some evidence suggests that the effect of the bentonite may reduce significantly over a number of years.

The mixing process usually produces large quantities of fine dust. Precautions should be taken to avoid inhaling dust particles.

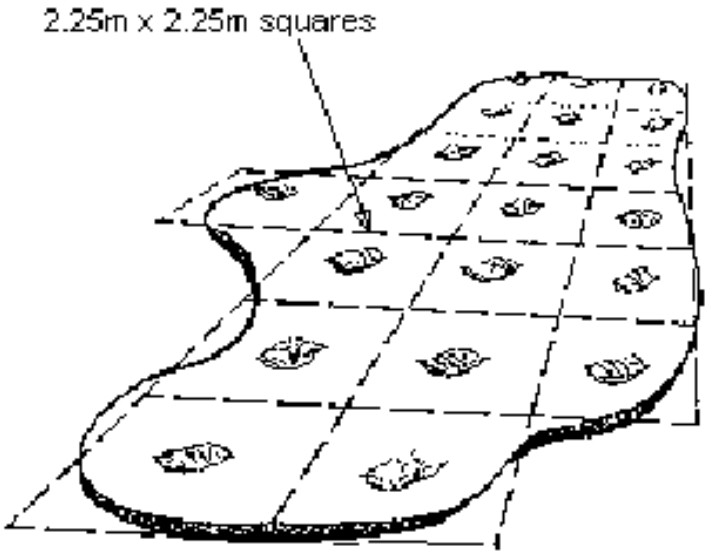


Figure 75: The mixed blanket method and peg out [44].

The pure blanket method

This method is suitable for both heavy or light soils. The procedure is [44]:

- Remove weeds, rocks and stumps. Level and lightly roll the area to be sealed.
- Spread a continuous layer of pure bentonite over the area with a hand rake to a depth of 25 mm
- Carefully cover this blanket with 150 mm of top soil, sand or gravel.
- Roll the whole area again.

This method has been claimed to reduce seepage by 95% or better. It also provides a solution to seepage in areas where cracking associated with heavy clay soils is a problem. Again there is evidence to suggest that the effect of the bentonite will reduce with time. Also, care must be taken when covering the bentonite layer to ensure it is not disturbed or penetrated by machinery. The method uses more bentonite than the mixed blanket technique, making it more expensive.

The dispersed blanket method

With this method applied to tailings storage, bentonite is spread over the surface of the tank or dam and allowed to settle to the bottom. In sinking to the bottom it is drawn into the cracks and seals them. A rate of at least 10 kg per square meter is needed and the granular form of bentonite is most suitable for this purpose. Results are variable and often unsuccessful due to insufficient bentonite being used. An indication of the quantities required is that for an enclosure of 20 meters in diameter, over 3 tons of bentonite should be applied.

The method is most suitable where there are isolated and obvious seepage points which require high applications of bentonite to seal them e.g. old dams and concrete tanks which leak through well-defined cracks or seams.

Injection/slurry trenching

Bentonite can also be used to form a cut-off wall by injection or pressure grouting and/or slurry trenching. These methods require specialized equipment and knowledge and are not commonly used. An indication of injection grouting is shown in the diagram below [44].

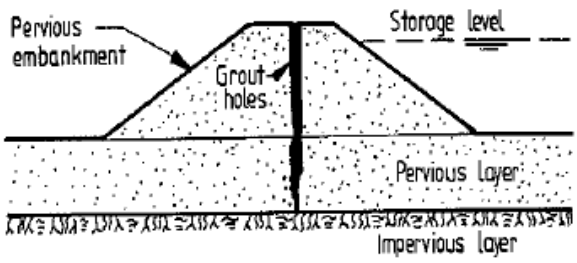


Figure 76: Sealing by bentonite injection [44].

Maintaining of the bentonite layer

When mixed with water, bentonite has a consistency similar to soft butter. Although highly impermeable, it can be easily disturbed, thus exposing the porous soils underneath. Disturbance may be caused by any of the following :

- erosion of the batters by heavy rainfall or runoff
- landslips on steep batters (i.e. on slopes steeper than 2½ horizontal to 1 vertical)
- strong water currents caused by pumping
- livestock wandering over batters
- cracking of soil cover after drying out.

The best protection for the bentonite layer is a thick cover of soil. A minimum thickness of 150 mm is recommended. Other precautions to take are :

- constructing catch drains around the storage perimeter to prevent excessive runoff on storage slopes.
- paving areas where inflow to the dam may cause erosion.
- fencing off vulnerable areas to livestock.

Sealing of the tailings pond ditch, road territory and upstream dam face (from pond water) is achieved using a bentonitic cushion (sodium montmorillonite combined with a geosynthetic material – under commercial names of Bentofix, Bentomat, etc.). Such cushions typically have a thickness of about 1 cm and a weight of about 5500 g/m^2, with a permeability coefficient of k = 5 x 10^{-11} m/s, being equivalent to a well compacted clayey layer of at least 1 m thickness.

The bentonitic cushion is interwoven over its whole surface and is fabricated from two geo-textiles, which encapsulate between them a sodium bentonite layer. Due to the interweaving process, the fibres are able to withstand and distribute shear effects, at the same time providing a sealed barrier for liquids and gases.

5.6.3. Sealing using other mineral materials

Mixtures based on slag and ash from power plants can also be used for sealing; they can be stabilized with different binders, for example having the following composition: slag (45-70%), ash (13-30%), lime (5-8%), calcium chloride (1.5%), water (10-15%), latex (0.5%). The permeability of the resulted stone is 2.6 x 10^{-8} cm/s, while the cost is relatively low.

Another solution is the use of double moulded walls, which ensure strict isolation of the seepage water from the tailing pond. Such thin walls are inserted by the vibratory-hammering of a special steel shuttering, and infilling with self-reinforcing mud during its extraction, with transverse walls so as to result a compartmentalized screen. Monitoring piezometers and inspection shafts allow the maintenance in the compartments of the water pressure level which is normally slightly higher than that in the pond, thus preventing any outward loss from the pond.

A modern solution to dam sealing is the utilization of HDPE geo-membranes (high density and with thickness of 2-2.5 mm) in the dam foundation, from the start of their construction, in association with geo-textiles for protection and drainage. The density of the 2-2.5 mm HDPE geo-membrane is 0.95 g/cm^3 while its weight is 2.5-3.5 kg/m^2, the permeability being around 10^{-14} m/s (i.e. practically impermeable).

TRISOPLAST

Among other materials used in tailings ponds stabilisation is TRISOPLAST® [115]. This is an innovative mineral sealing material that offers a number of significant benefits when compared to traditional mineral liners. It was developed in the Netherlands to technical maturity and successfully tested for performance and usability by independent testing laboratories. Since 1992 an increasing number of European countries have approved TRISOPLAST as a sealing barrier for various applications and as a result it is a commonly preferred option. Independent testing and ongoing research have already confirmed its performance.

TRISOPLAST®. is a registered trademark. The system was developed by TRISOPLAST® Mineral Liners and is protected by patents. TRISOPLAST® is produced under the license of RISOPLAST® International [115]. TRISOPLAST® consists of the following main components:

- Granular material, e.g. sand
- Bentonite
- Polymer

The components are combined in mixing plants and small amounts of water are added if required. Thus TRISOPLAST. is installed and compacted at water contents close to but below the proctor optimum. In a first step the bentonite powder and polymer powder are blended; secondly the sand and bentonite-polymer pre-mix are combined in a forced mixer to achieve a homogeneous material.

In order to control the dosing of the components the water contents of the bentonite and the granular component must be determined in advance and taken into account when calculating masses for the correct settings of the mixing plant.

The finished mixture is loose, has a granular appearance and is free of lumps and easy to handle. The TRISOPLAST. mixture is handled and compacted with conventional earth construction equipment (telescopic or long-reach excavators and rather light, smooth drum rollers or compactors) in a single layer on a well prepared subgrade of sufficient load bearing capacity. The initial moisture content at mixing causes immediate binding within the laid material, resulting in a cohesive medium suitable for creating a well compacted layer.

A unique clay-gel is formed from a mixture of sodium activated calcium bentonite and polymers, as soon as additional moisture reaches the applied layer. A very compact gel structure is developed by the network of chemical compounds formed by the clay mineral particles and the polymers.

The granular component must meet the following specification before being accepted for the production of TRISOPLAST® [115]:

- Mineral particles 0.063 mm < 10% by dry mass
- Mineral particles > 4 mm 0.5% by dry mass
- Mineral particles > 5.6 mm 0.1% by dry mass
- 50% particle diameter (d50 or M50) 0.15 mm - 0.7 mm
- Organic matter content < 1.5% by dry mass
- Calcium carbonate 5% by dry mass
- Hydrogen ion activity (pH) 4.5 - 10.0
- Electric conductivity < 1000 S/cm
- Chloride < 600 mg/kg dry mass

The granular component may not contain any sharp edged or foreign particles, such as building rubble, lumps of loam or roots.

The granular component (sand) must be of the same quality and must come from the same source/location as used for the pre-investigation testing. Every batch of sand supplied must be accompanied by a certificate of origin, issued by the producer of the sand. This certificate of origin must state the name of the producer, the nature and source of the sand.

Maximum grain size can be increased to 8 mm if the local regulations permit larger particles in combination with a geomembrane or when used on its own (the above mentioned requirement derives from the Dutch membrane regulations for subgrade and covering layers).

TRISOPLAST specifications: bentonite

The sodium-activated calcium bentonite must meet the following specifications before being accepted for the production of TRISOPLAST® [115]:

- Montmorillonite content: 70% by dry mass
- Methylene blue test: 200 mg methylene blue / g bentonite
- Mineral particles: 0.125 mm: 5% by dry mass
- Water content: 13% by mass related to the dry mass
- Swelling capacity: 25 ml/2 g
- Water absorption capacity after 24 h > 450% (Enslin-Neff) or > 700% (Enslin or Cur 33) with distilled water (by mass) related to dry, sodium-activated bentonite.

The bentonite must be of the same quality and must come from the same source / location as used for the pre-investigation testing. Each batch of bentonite must be accompanied by a certificate of origin, issued by the producer of the bentonite. This certificate of origin must state the name of the producer, the name of the product, the type and source of the bentonite.

TRISOPLAST specifications: polymer

The polymer is exclusively delivered by TRISOPLAST® Mineral Liners who developed TRISOPLAST® and obtain the polymer from a certified supplier. The supplier produces the polymer exclusively for TRISOPLAST® Mineral Liners and has confidentially received all necessary requirements and process descriptions necessary for the polymer production. The uniform properties of the Polymer are demonstrated and can be checked by the following characteristic properties:

- Viscosity: Based on the internal test description of the manufacturer of the polymer
- Solubility: Based on the internal test description of the manufacturer of the polymer
- Particle size distribution: Sieve analysis based on DIN 18123
- Infrared analysis: Qualitative evaluation of the spectrum
- Content of two characteristic elements: Standardised elements analysis

The manufacturing process of the polymer, the methods of storage and transport, the requirements it must meet for quality testing and the test descriptions have been assessed and approved by the German Federal Institute for Materials Research and Testing (Bundesanstalt für Materialforschung und -prüfung, BAM) in Berlin.

Polymer deliveries by the producer and afterwards by TRISOPLAST® Mineral Liners are subject to quality control tests, including testing of the characteristic properties of the polymer and testing of samples by ATO-DLO (University of Wageningen, NL) to confirm itsconformity to the specified polymer. This is in accordance with the methods assessed and approved by BAM.

Before mixing with the bentonite a sample of polymer is taken from each 1000 kg of polymer delivered, and is stored by TRISOPLAST® Mineral Liners or its licensee for at least two years. By means of this sample, there is an ability to further test the properties and conformity of the polymer employed, if extra investigation additional to the standard quality control tests is required.

The polymer is supplied to the mixing facility in big-bags with a plastic cover to give an extra protection against negative weather influences. The packed big-bags must be transported and stored in dry conditions.

TRISOPLAST Specifications: water

The added water must meet the following requirements before being accepted for the production of TRISOPLAST® (drinking water normally meets these requirements):

Conductivity: 1,500 S/cm

Acidity (pH): 5.0 - 9.0

Mixing water absorption capacity of the dry, activated bentonite after 24 h: > 385% by dry mass (Enslin-Neff) or > 600% (Enslin or CUR 33) Swelling capacity of the dry, activated bentonite in the mixing water: 22 ml/2 g.

TRISOPLAST® Layer Performance

As with every natural mineral barrier material, the tested property values vary between certain boundaries.

In order to guarantee that the minimum performance requirements of the sealing system are met, it is necessary to specify certain properties of the barrier. TRISOPLAST® can be installed at various thicknesses (normally these lie between 5 and 10 cm, for practical and safety factor reasons it is recommended not to go below 5 cm). It generally reaches permeabilities in the range of $k < 1 \times 10^{-12}$ m/s to $k < 3 \times 10^{-11}$ m/s. The Dutch regulation (see below) for example specifies the tolerable leakage rate over a given period of time under certain environmental conditions. As a result of that, the maximum allowable permeability at a specified thickness can be derived).

For instance, a mineral barrier used in a landfill cap is allowed a maximum leakage of 20 mm per year in accordance with the Dutch Standard Design conditions for landfill liners. A water column of 0.5 m on the top, a negative pressure of 50 mbar at the bottom and a leakage period of 200 days/year are assumed.

A layer thickness of 0.07 m results in a hydraulic gradient of i = 15.3 and a permeability requirement of $k < 7.57 \times 10^{-11}$ m/s. For basal lining in the Netherlands the thickness is chosen at 0.09 m and a water column of 0.5 m on the top and a negative pressure of 50 mbar at the bottom are assumed, over a period of 365 days/year, resulting in a gradient of i = 9.89 and a permeability requirement of $k \leq 6.41 \times 10^{-11}$ m/s.

In the above cases the TRISOPLAST® layer shall be installed with a minimum average layer thickness (after compaction) of 0.07 m or 0.09 m respectively. The locally permitted negative tolerance of the total layer thickness should generally be limited to -0.02 m. It has been demonstrated successfully on a large number of projects throughout Europe that the above mentioned thickness requirements can easily be met.

Some aspects of TRISOPLAT installation are illustrated below.

In many respects a TRISOPLAST seal is superior to conventional mineral seals or GCLs (geosynthetic clay liners).

Equivalency has been proven based on the DIBt guidelines for landfill covers by the independent working group TRISOPLAST (12 Landesämter fur Umwelt, UBA, BAM chaired by the Niedersachsiches Landesamt fur Ökologie, Hildesheim): 7 cm TRISOPLAST are equivalent to a 50 cm thick mineral barrier according to TASi.

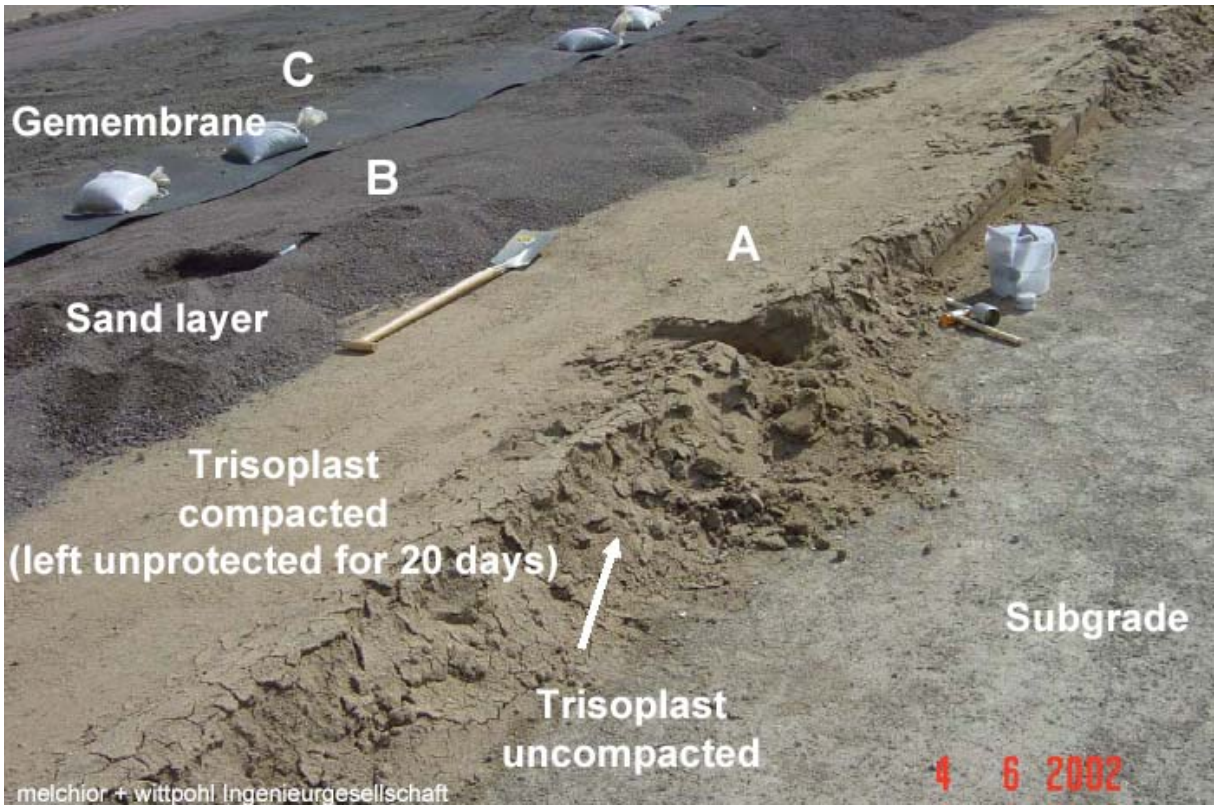


Figure 77: TRISOPLAST covering works [115].

Figure 78: Installation of TRISOPLAST [115].

Figure 79: Installation of TRISOPLAST [115].

Figure 80: Installation of TRISOPLAST at Malaieni tailings dam (Romania) [115].

Figure 81: Installation of TRISOPLAST at Malaieni tailings dam (Romania) [115].

Other materials – miscellaneous:

Other less practical, higher risk or more expensive dam-sealing options include:

- Sodium tri-polyphosphate (STPP);
- Bitumen reinforced with glass-fibre; and
- Concrete reinforced with wire netting or steel mesh.

STPP is a powerful dispersing agent which is a common ingredient in washing powders. At recommended rates and methods of application, STPP has successfully reduced the seepage rate from leaking farm dams in mottled zone and pallid zone soils.

Reduced seepage results from the collapse of soil structural units and subsequent blocking of soil pores, due to increased mobility of soil particles. However, in approximately 20% of treated dams, the supervised application of STPP at recommended rates may lead to greatly increased seepage due to induced 'piping' failure.

Use of STPP in leaking dams is regarded as too risky, unless experts are available to specify, design and supervise the project.

The last two methods (i.e. reinforced bitumen or concrete) employ materials used widely in the construction industry. Although the methods and materials are highly dependable, successful application requires strict adherence to engineering construction specifications.

5.7 Dam consolidation works

5.7.1. Enforcement with geo-grid (geo-synthetics)

Geo-grids represent a rapidly growing segment within the geosynthetics area. Rather than being a woven, non-woven or knit textile (or even a textile-like) fabric, geogrids are plastics formed into a very open, grid like configuration, i.e., they have large apertures. Geogrids are either stretched in one or two directions for improved physical properties or made on weaving machinery by unique methods. They function almost exclusively as reinforcement materials.

Geo-networks, at first sight, have a similar structure to geo-grids but with a basic rhombus form and angles which generally vary between 70° and 110°, and with thickness of 5-10 mm. They are fabricated from extruded strong ribs, extruded ribs from spongy polymer (with greater thickness and therefore gaps with a higher flow capacity) or from drawn strong ribs (with intersections at right angle, for increased resistance).

The geo-networks are generally formed from polyethylene, with the addition of about 2% smoke black (for the protection against UV rays) and 0.25-0.75% additives (antioxidants, lubricants).

In their anti-erosion function, the geo-networks are utilized for the protection of slopes, with vegetation or without, the geo-networks being usually associated with other mineral or geo-synthetic materials. They may have only a temporary role until vegetation develops, or a permanent role, in conjunction with the vegetation, thereafter.

Geo-nets, called geo-spacers by some, constitute another specialized segment within the geosynthetic area. They are usually formed by a continuous extrusion of parallel sets of polymeric ribs at acute angles to one another. When the ribs are opened, relatively large apertures are formed into a net like configuration. Their design function is completely within the drainage area where they have been used to convey fluids of all types.

As concerns endurance of geo-networks, we are interested in long-term deformation and the ability of the geo-network to continue to provide passage for a liquid, in light of three parameters: yield under stress; obstruction of flow section due to adjacent materials penetrating openings; and particulate material escaping through the geo-textile which covers the geo-network).

Geo-networks are utilized in the context of tailings ponds, both in the collection and discharge system for their basal flows and finally for the covering system. In these situations, the geo-network can be found either between two geo-membranes (one forming the primary seal and the other a secondary seal for detecting leakage flows) or between a geo-textile and a geo-membrane (the geo-textile serving to ensure drainage and hence a low hydraulic gradient on the geo-membrane.

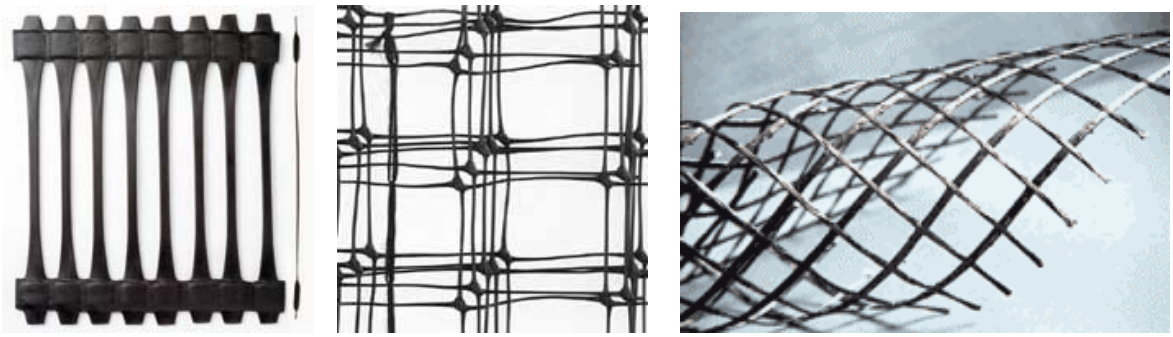


Figure 82: Types of geo-grids (left and center: http://www.tenax.net/geosynthetics/, right: http://www.mirafi.com/).

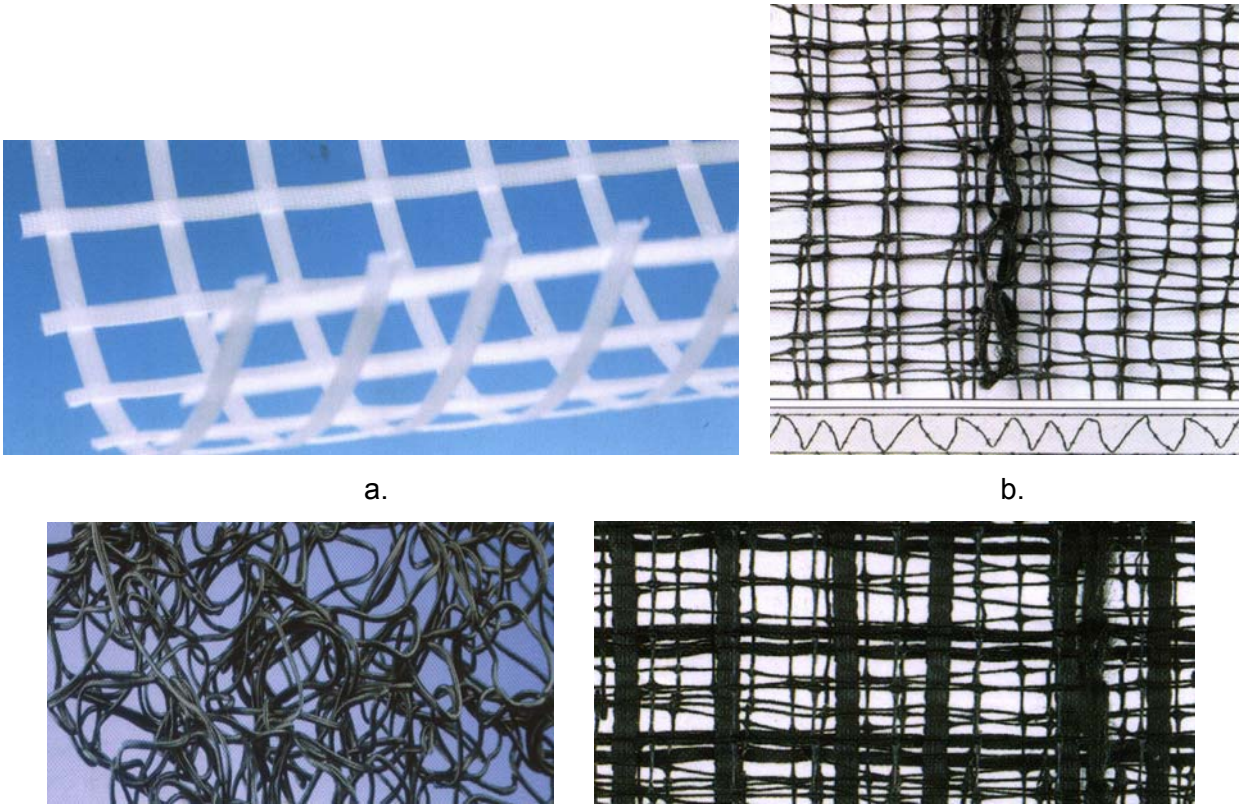


Figure 83: Constructive types of geo-network (a. and c. company prospect Naue, Germany; b. and d. company prospect Tenax, Italy).

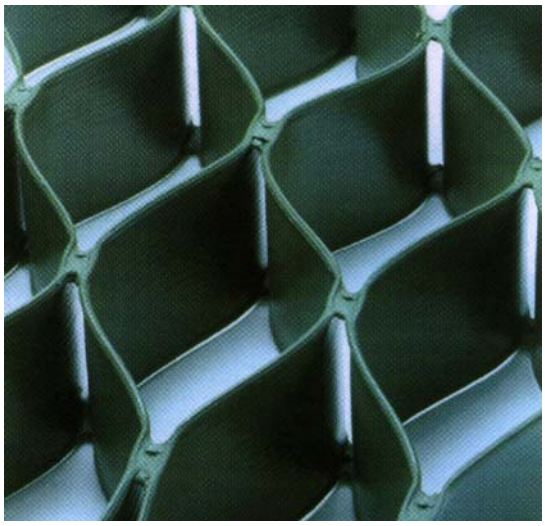


Figure 84: Geo-net (Source: company prospect Tenax, Italy).

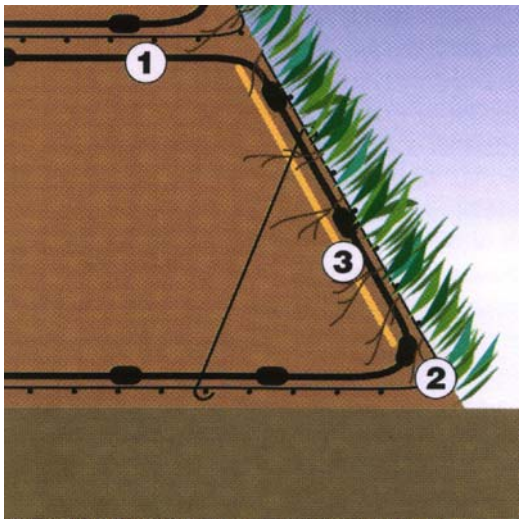


Figure 85: Reinforcement of slope by geo-net (Source: company prospect Tenax, Italy).

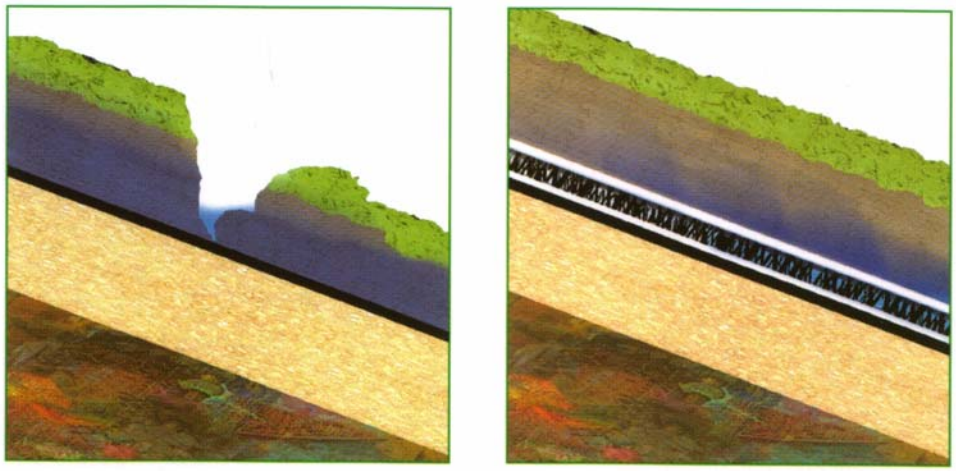


Figure 86: Influence of Geo-net on slope stability (Source: company prospect Naue, Germany).

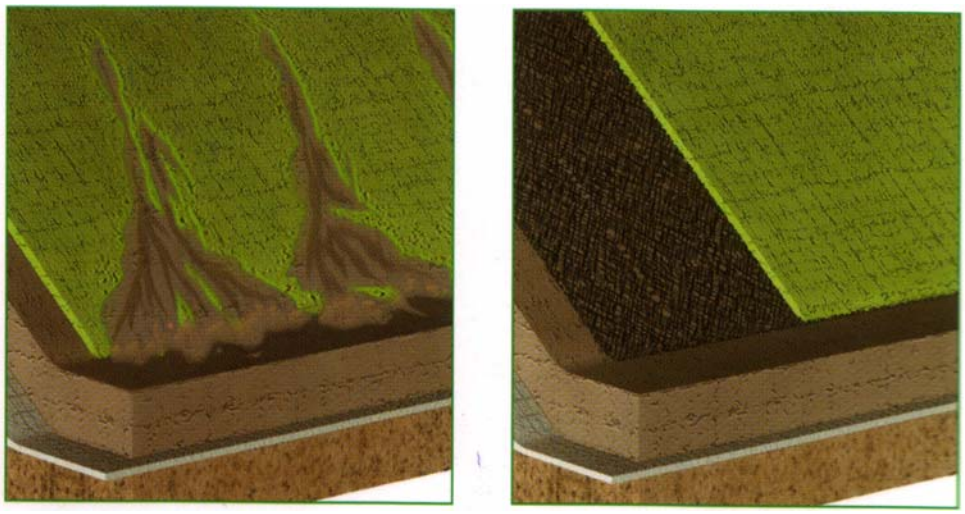


Figure 87: Influence of geo-net with vegetation (Source: company prospect Naue, Germany).

Geo-networks are also utilized in order to prevent the erosion of an embankment surface (on the downstream slope), presenting the advantage that they do not absorb humidity, their dimensions do not alter as time goes on, and they allow vegetation nutrition from the ground.

The geo-networks can be associated with a geotextile (i.e. in a geo-composite), the geotextile being placed over or under the network, or the geo-network being placed between two geotextiles, performing filtration, separation and drainage functions.

Geo-grids are geo-synthetic materials, generally utilized for earth reinforcement, fabricated from a regular network with meshes large enough to allow the penetration of the materials they come into contact with. The holes have much bigger sizes (1-10cm) than the ribs sizes.

Incorporated in the earth or in any other material, the geo-grids work thanks to the network/material friction on both sides and to their mechanical interaction with the host material.

There are two basic sorts of geo-grid: octagonal networks made from thin bars fixed one with the other at nodes; and octagonal polymetric strips superposed by a special process of extrusion and stretching (they can be mono- or bi-stretched).

The achievement of support structures by reinforcing ground with geo-synthetic materials is becoming more and more frequent. Such reinforcement is a solution which can be used in the strengthening of tailings ponds by the geo-grids arrangement the geo-grids in vertically equidistant layers (0.5-1 m depending on the characteristics of the reinforced material). The stronger geo-grids (about 28 KN/m) are used at the base of the dam or deposit and lower strength grids (about 20 KN/m) in their upper levels. On the downstream side there are various solutions which can be used to fix the ends of the reinforced support structures:

- prefabricated concrete slabs, with end pins for connecting the geo-grids;
- concrete slabs poured on the site; the geo-grid ends are turned at ground level so as to form its protection, the slabs being poured over the geo-grids ends;
- downstream face of the dam with small blocks, with geo-grids being fixed with special devices between the blocks;
- gabions, with cages made from polymers or wire and filled with stone, the geo-grids being placed between the gabions.

The downstream side of the dam may be protected against erosion by geo-networks in association with geo-synthetics or with geo-cells (see below) and mineral material.

5.7.2. Reinforcement with geo-cells (geo-synthetics and mineral materials)

Geo-cells are a cellular confinement system in an expandable three-dimensional polyethylene, honeycomb-like structure that provides cost-effective solutions to slope and channel protection, load support and earth retention applications. It is used in landfill cover applications, detention pond protection, dam face protection and channel lining systems.

Structural, they are three-dimensional cushions, achieved from geo-grids, from geo-textile or polymers strips.

Geo-cells made up from geo-grids take the form of a cell complex of triangular or quadratic section, with base and walls built from geo-grids filled with gravel. They allow maximum utilization of the grids' supporting stability in conditions of soft foundation soil and ensure a strong and stable operating platform for earth-works equipment.

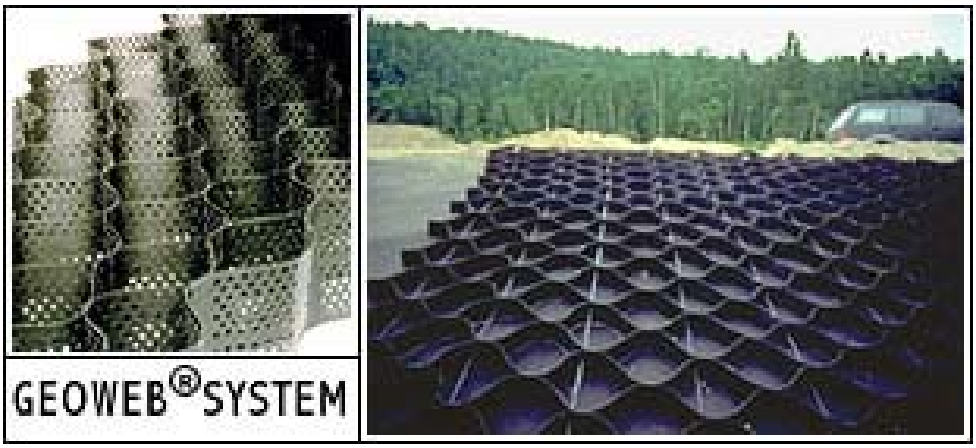


Figure 88: Types of geo-cells (Source: http://www.geocheminc.com/geoweb1.htm).

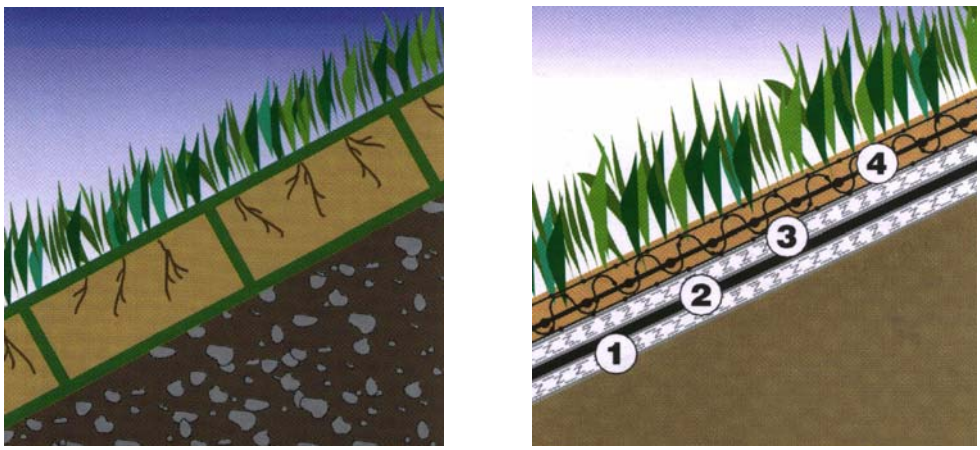


Figure 89: Geo-cell placing methods (Source: company prospect Tenax, Italy).

The geo-cellular cushions must have the following mechanical characteristics:

- stretching resistance high enough to allow the integral mobilization of shearing resistance from the base of the material;
- rigidity high enough to assure a practically uniform distribution on the foundation soil;
- significant friction at the cushion underside, due to the partial penetration of the coarse filling into the meshes of the lower geo-grid.

Due to the presence of the geo-cells (cushion), the stress state in the soft soil alters by the reorientation of the main planes and the possible surfaces of failure by sliding, so as to predominate in the respective material, the forming conditions of plastic zones, beginning from the marginal parts of the cushion.

The structural resistance of the cushions depends on the shape and size of the cells, as well as the distance between their walls. Thus, the stretching resistance of a cushion with triangular cells is higher than in the case of the quadratic cells. A triangular cell is effectively achieved by the inclusion of a diagonal wall within a quadratic cell, in this way increasing the number of geo-grid diaphragms per unit length.

A significant role in the mechanical quality performance of the cushions is accomplished by the basic geo-grid interaction with the soil, expressed by the friction between the two materials.

Under the action of the loads produced by an embankment under construction, an evolutionary stress state appears in the soft soil layer situated under the cushion, emanating from the base of the embankment. As the loads increase, the plastic zones which appear at the embankment extremity amplify, advancing towards the interior, till they reach its central zone. At this stage, the soft layer is under an equilibrium stress state, in which the tangential stress at the cushion/soil interface becomes equal to the material's shearing resistance. The relatively low rigidity of the geo-cellular cushion assures the integral mobilization of this resistance on the entire breadth of the plastic zones.

Geo-cells made up from geo-textiles are used to reinforce soft foundation soils and are fabricated from geo-textile or polymer strips (HDPE). At delivery, they are gathered like an accordion, being unfolded on the site and afterwards filled with mineral material (sand, granular material, etc.).

The high density polyethylene strips (HDPE) are joined ultrasonically, in order to form cells in a honey comb type structure. This system can be used within dam structures (i.e. as reinforced soil works), in slope protection against the actions of precipitation, storm flows, ex-filtration, wind, waves, or water flows (i.e. as anti-erosion works), on the faces of barrages and dams (i.e. for the protection of upstream or downstream sides), and in special concrete constructions (i.e.

as blocks against piping, geo-cells may be filled with concrete under water, the geo-cells playing the part of formwork too).

By installing three-dimensional geo-cells on slopes, the material of the dam may be fixed in a cellular system and stabilized, hindering its dislocation, sliding and wash-out. The system conducts the water flow over the cells rather than through them and maintains humid conditions in the cells' interior, in this way preventing swelling and destabilization.

In the case of soils with low sliding resistance, the slopes can be erosion protected with gravel poured into such cellular units. In rainy weather, with the danger of storm flows, the gravel absorbs the energy and slows the hydraulic discharge in the interior of the geo-cells system and below it. The geo-cells can be used for the erosion protection of slopes having an angle of inclination of over 30°. The geo-cells are resistant to the action of UV radiation, having been tested by exposure to solar radiation for 9 months (they would normally be covered within that period). They are resistant to the action of chemical and bacteriological agents.

6 Case studies

6.1 Rock riprap - case studies

Envirocon constructed a stream diversion around mine tailings at a former cobalt mine that operated between 1900 and 1967. The mine was located 45 miles southwest of Salmon, Idaho at an altitude of 5,700 feet. Approximately 2 million tons of mine tailings had been deposited as slurry in a tailings impoundment on a creek bed. Creek flows were originally routed through a concrete pipe installed beneath the tailings.

Figure 90: Water Channel for diversion of creek water [11].

Over time, the integrity of the pipe was compromised and a diversion was proposed to prevent trace metals in the tailings from contacting the stream flow.

The primary element of the scope of work was the construction of a 2,200-foot long channel capable of carrying over 2,000 cubic feet per second of water. The channel was 12 to 25 feet deep, 18 feet wide at the bottom, and between 66 and 100 feet wide at the top. The channel profile required excavation of 50,000 cubic yards of tailings materials and an additional 50,000 yards of borrow to complete. The channel was lined with 2 feet of impermeable clay, covered with a non-woven geotextile, and topped with 2 feet of riprap.

In addition to the channel, a concrete spillway was constructed to divert water over the dam and connect it with the main fork of the creek. Spillway construction required excavation of 16,000 cubic yards of material, of which 5,000 cubic yards required blasting. The spillway was a stair-step design and was secured to the bedrock using anchor bolts. Each spillway bench was approximately 40 feet wide, 33 feet long, and 23 feet high on the upstream side. A total of 750 cubic yards of concrete were mixed with a portable batch plant and used in the construction of the spillway.

In addition to the channel and spillway, Envirocon constructed a buttress for the tailings dam and a new access road to comply with more stringent earthquake standards. The tailings dam buttress and access road required over 100,000 cubic yards of borrow placement. A 200-foot cement/bentonite slurry wall was also installed upstream of the diversion trench to cut off groundwater flow into the tailings and pre-existing concrete pipe. The wall followed the bedrock profile and was constructed to a depth of 25 feet [9].

6.2 Sheet piling - case studies

At an abandoned mine in the Yukon Territory, mining for both Gold and Zinc took place until the mid 1950s, with the processing of the ore taking place on the banks of an adjacent lake. Processing methods resulted in the creation of a large mine tailings pond that had high concentrations of iron, arsenic, zinc and lead. Spring runoff and summer rainfall then infiltrated through the pond resulting in contamination of the lake with heavy metals. The lake is a primary source of drinking water and the prevention of further contamination of this water supply was required as part of the an aboriginal land settlement claim.

The site remediation plan was based upon the installation of a vertical Waterloo Barrier® cut-off wall along the down gradient side of the former tailings pond to act as a barrier to prevent contaminated ground water from entering the lake.

Figure 91: Site overview [19].

Approximately 12,000 square feet of Waterloo Barrier® WZ75 sheet piling was installed, in varying depths (from 25 to 15 feet), following the bedrock profile along the down gradient side of the former tailings pond. As can be seen in Figure 92 the preparatory geotechnical work was very beneficial as only one unexpected rock outcropping was encountered.

Figure 92: Installation of sheet piles as Waterloo Barrier® [19].

The joint sealing operation was completed in two phases. During the first phase, a mechanical packer was inserted to the base of the sheet pile joint and once inflated the sheet pile/bedrock interface was pressure grouted. During the second phase, standard joint grouting operations were completed using a silica fume modified cement grout (WBS-301) to seal the joint on the sheet piling.

6.3 Dewatering - case studies

6.3.1. Dewatering by wells

Slime dewatering at the Homestake's Grants Project (uranium mill tailings)

The challenge was the dewatering of a tailings pile containing 22 mt of uranium mill tailings. Tailings had been formed in a mill operated during the period 1958-1990. Hydraulic tailings deposition at this site has resulted in segregation of the silt and clay particles (slimes) in the centre of the pile's two cells.

The outer dyke was constructed by cycloning the tailings with deposition of sand material, forming outer dikes and slimes flowing to the inside of the dikes to ponds. The perimeter edge of the tailings therefore was composed primarily of tailings sand, while the inner portion of tailings consisted mainly of slimes. Sand and slime lenses were present in areas dominated by

the other end of the milled tailings gradation spectrum, but two large areas, mainly slimes existed at that site. Pools of water were maintained in the west and east cells during the operation of the Grants mill. Recontouring of the large tailings began in 1993 and was completed in 1994. Tailings wells were drilled in 1994 and 1995 to define the hydrologic conditions in the tailings. These wells were used to define the saturated level of the app. 27 m thick recontoured tailings. The tailing facility has a saturated zone up to 23 m.

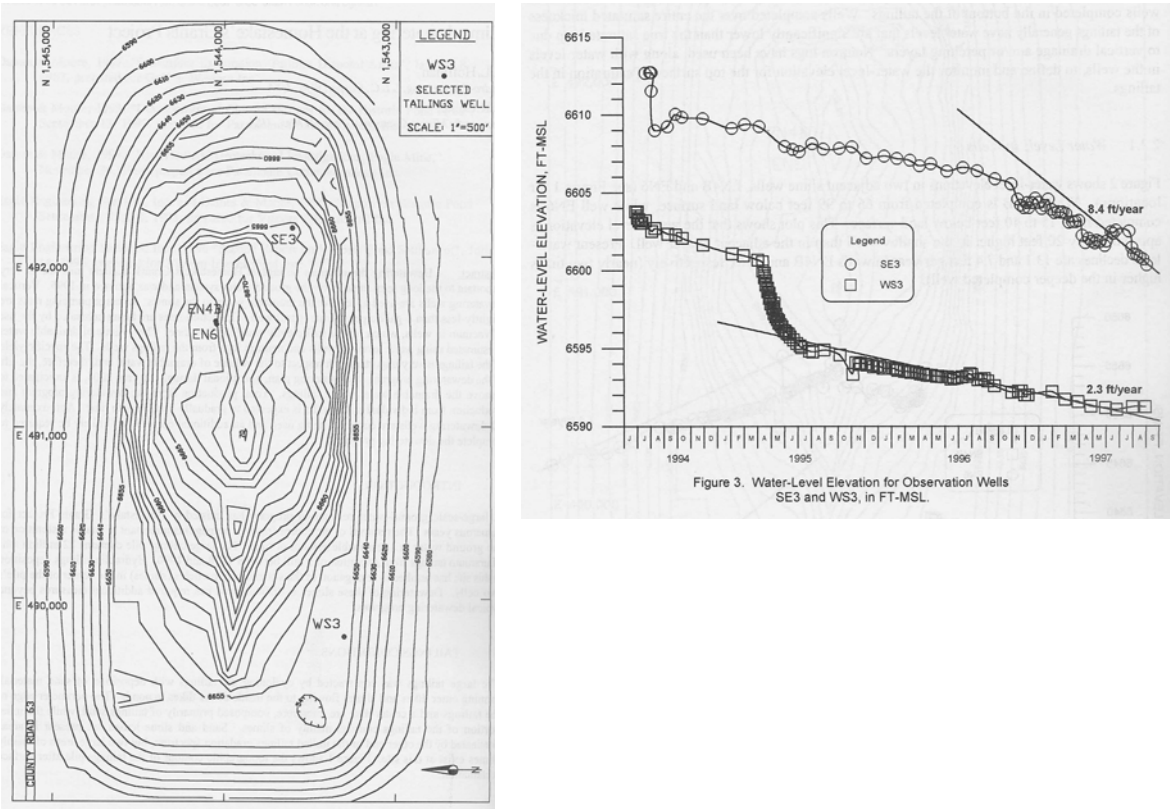


Figure 93: Topographic contour of Homestake's Grants tailings facility after surface reclamation with selected well locations (left) and the observed water level elevation (right) [51].

After completion of the surface remediation, wells were drilled and water removal started. In Figure 93 (right) it can be seen that in the well WS3 located in the sand dike the water level declined very sharply in the first few months. Later the rate of water level decline has gradually decreased with an overall current rate of decline of 2.3 feet (0.7m) per year. The very gradual decline in the water level shows that drainage from the slime area into the sands in that area has maintained higher water levels than would be expected from the pumping of nearby wells. The figure also shows that the water level in well SE3, which is mainly draining slimes. Since late 1996, when a large number of dewatering wells were placed into operation, the water-level decline rate has been 4 feet (1.21 m) per year (Figure 93).

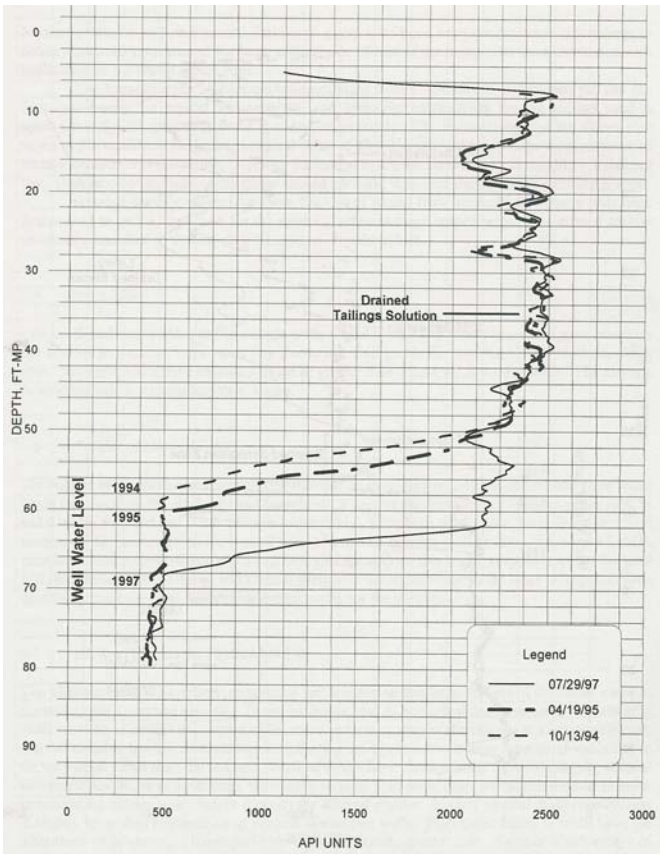


Figure 4. Neutron Logs for Well WS3.

Figure 94: Decreasing of saturated zone [51].

In many cases, decreasing in the water levels shows that dewatering of tailings took place, because the saturation zone in the tailings has decreased. Location of the saturated zone has been defined using neutron logs in the wells. The consistency of the neutron log over the period of record for depths up to approximately 50 feet (15 m) indicates complete drainage of these sand tailings (Figure 94 for well WS3 located in sand dike).

A similar picture was observed in well SE3, which is completed primarily in slimes. Saturation initially existed below the 10 to 15 foot (3-4.5 m) interval in 1994, even though the water level in the well was 55 feet (16.7 m) below the measuring point. The saturation interval in 1995 had dropped to approximately 36 feet (10.9 m) with some drainage still occurring in the interval above this depth. The saturation interval by 1997 was approximately 50 feet with some drainage of the materials below the 50 feet interval. Additional drainage of water from above the saturated zone, with time, is still likely to occur. The transmissivity of the sand tailings ranges from a few tens to 4000 gallons per day per foot (gal/day/ft), but with a typical transmissivity approximately 200 gal/day/ft.

The transmissivity of the slimes also average a significant range, but a typical value of 40 gal/day/ft is thought to be representative of average conditions in slimes. Average horizontal hydraulic conductivity for slimes is roughly 0.1 feet per day. Hydraulic conductivity of slimes should decrease with time during the dewatering process.

Average specific yields (drainable fraction of water) from the multi-well pump test were determined to be 0.14 and 0.08 for the sand and slime tailings, respectively. Unconfined aquifer test theory was used in determining these specific yield values.

The predicted well yields for the tailings wells varied from a few tenths to several gpm, based on the aquifer properties. Experience has shown that well yields do vary from a few tenths to a few gpm. Very few wells have sustained a rate of greater than 2gpm for several months. The average dewatering rate is slightly less than 1 gpm (6.5 m^3/d). The volume of drainable water has been estimated from the saturated interval determined from water levels from wells in the sand area and from neutron logs in the lime areas. The calculated total volume is 836,000 m^3.

Phatfinder Mines Corporation - Shirley Basin Mine

Arnold (1999) used diversion wells for AMD treatment in PA and reports that three wells increased pH from 4.5 to 6.5, with corresponding decreases in acidity. For example, one diversion well located at Lick Creek treats about 1000 L/min of slightly acid water. After passing through the diversion well, the pH changes from 4.5 to 5.9 and the net acid water (8 mg/L as $CaCO_3$) changes to net alkaline water (6 mg/L as $CaCO_3$). Similar results are found for several other sites in PA. A diversion well has also been constructed in the Casselman River Restoration Project (Ziemkiewicz and Brant 1996). This large diversion well has a retention time of about 15 min for a 360-L/min flow of moderately acid water. The diversion well reduces the acidity from 314 to 264 mg/L as $CaCO_3$, Fe from 83 to 80 mg/L, and Al from 24 to 20 mg/L.

At the Galt site in WV, a diversion well changes a 20-L/min flow from a pH of 3.1 to 5.5, acidity from 278 to 86 mg/L as $CaCO_3$, Fe from 15 to 2 mg/L, and Al from 25 to 11 mg/L (Faulkner and Skousen 1995).

6.3.2. Dewatering by loading - case studies

The practice of stabilisation and dewatering of fine tailings is well established. This is due to the huge volume of fine tailings in the mining industry. The grain size distribution of the tailings being deposited has become very fine over the past decades in some industries. For example in the gold mining industry, the grain size distribution of tailings 20 years ago was about 70

percent finer than 200 mesh screen size. Now it is typically between 90 and 95% finer than the 200 mesh screen size [49].

Case study: WISMUT uranium mine tailings

Tailings pond remediation aims to achieve the safe long-term storage of tailings by isolating them from the atmosphere, biosphere and hydrosphere as much as possible. The techniques applied to achieve this must ensure that emissions via air and water pathways are minimized to comply with regulatory requirements. The uranium mine tailings of the former Soviet-German mining company WISMUT provide an interesting case in point.

While immediate hazards were mitigated, ongoing studies integrating world-class environmental restoration technologies investigated various remedial options for achieving long-term stabilization of the tailings ponds. As a result, dry in-situ stabilization with partial dewatering of tailings was selected as the most appropriate option. Further planning will be based on this general approach, while design details (contouring, covering, seepage collection, vegetation, etc.) have to be optimized for each tailings pond under consideration [125].

Tailings pond stabilization will involve the following steps:

- Removal, treatment and discharge of supernatant pond water,
- Interim covering of exposed tailings areas,
- Regrading of dam and tailings surfaces,
- Final covering of contoured surfaces,
- Landscaping and revegetation,
- Collection, treatment and discharge of seepage, and
- Long-term monitoring.

The cover is designed to minimize both radon exhalation and the infiltration of precipitation. It is a multiple-layer system that is placed in two phases [125]. During the first phase, an interim cover is put in place consisting of man-made materials such as geo-fabric, drain mat, or geo-grid on which typically waste rock material will be placed. The additional loading of such material, which also acts as a drainage layer, accelerates the desired partial tailings dewatering. This effect is enhanced by the installation of vertical drains (wicks), which are typically driven down into the tailings to a depth of 5 m. During the second phase, at the end of essential consolidation (settlement) processes, the final cover is placed using subsoil and topsoil.

Removal of pond water is a prerequisite for tailing pond stabilization. Radio-nuclides and arsenic contained in the supernatant and pore waters of the WISMUT uranium tailings had to be removed and immobilized. A water treatment plant installed at the Helmsdorf site to treat water

from the Helmsdorf and Dänkritz 1 tailing ponds has been on stream since mid-1995. By the end of 1999, this facility had treated some 7 million cubic meters of pond water prior to discharge into the Zwickauer Mulde river. As a result, by December 1999 the water level in the Helmsdorf pond had been lowered by more than 5 meters from its peak level in 1995. Immobilized residues from the water treatment process are deposited in an engineered area at the Helmsdorf tailing facility, where they will be encapsulated as part of the final cover construction.

Design of the final shape of the tailings impoundment surface is one of the main tasks in preparation for rehabilitation. Given the required long-term cover performance, and for cost-efficiency reasons, preference is given to natural materials available on site or in the immediate vicinity of the site. Landscaping plans for the rehabilitated tailings facilities are finalized in consensus with local and regional bodies.

Concepts for landscaping and after-use of the Helmsdorf, Dänkritz 1, Culmitzsch and Trünzig tailings facilities [125] were agreed with regulatory agencies, communities, and other stake-holders. These concepts served as a basis for planning the contouring work, which at the Trünzig tailings site started in 2000.

The reclaimed areas are to be integrated into nature conservancy schemes. The design will be that of a nature-oriented landscape, comprising green spaces and water bodies. These water bodies with sealed bases will serve as retention ponds for surface-water runoff, which must not infiltrate into the covered tailings. Reclamation is aimed at walk-away schemes demanding minimum care and maintenance. Finally, the environs of the reclaimed tailings facilities are to be afforested.

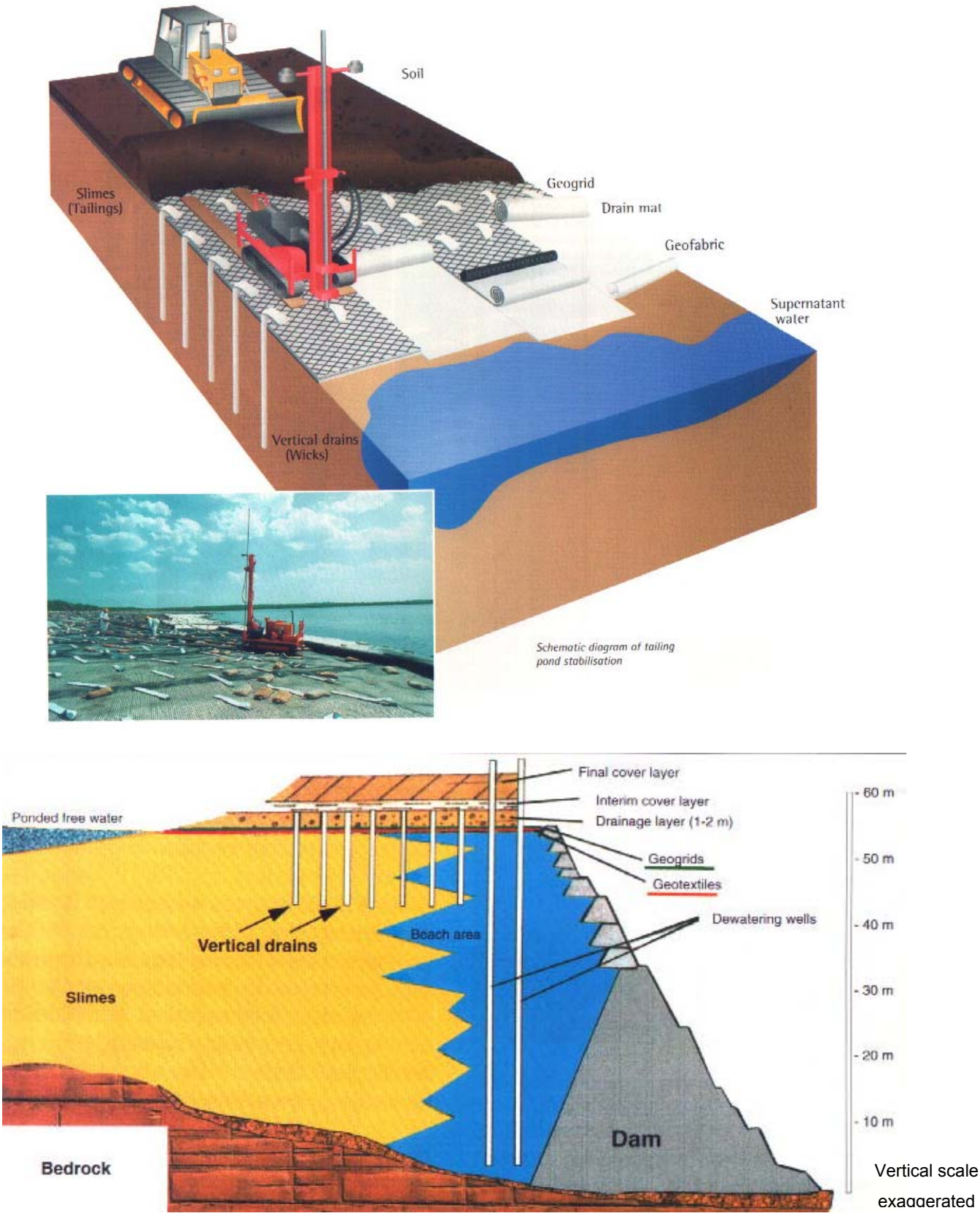


Figure 95: Dam sealing works [125].

Figure 96: Dam sealing works [125].

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