TAILSAFE

Sustainable Improvement in Safety of Tailings Facilities

TAILSAFE

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Report

Implementation and Improvement of Design and Authorisation Procedures for Proposed Tailings Facilities

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Tailings Management Facilities – Implementation and Improvement of Design and Authorisation Procedures for Proposed Tailings Facilities

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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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1.1 General Tasks

Planning and Installation of Disposal Facilities must guarantee that a discharge of pollutants into biosphere is within an acceptable level. The choice of a storage conception basically depends on both, the properties and the environmental impact of the tailings as well as the topographic, hydraulic and geological conditions. The engineering properties are divided in specific characteristics of the strength, drainage conditions and the ability to spread or retain contaminated material. Groundwater protection and stability of the subsoil, the retaining dam and the tailings are the main marginal conditions for planning a Tailings-Settling-Basin. Reason therefore is the usually high risk potential of such a dump because of its stored contaminated material.

Objective of a site investigation is to obtain the most complete and accurate estimate possible for the location, the extent and the engineering character of the soil and the rock, underlying the basin and the impoundment, with regard to the limits of time, money and practicality.

Kind and extent of the site investigation depends among others on factors like topography, morphology and infrastructure of the site, sort and behaviour of the tailings and geological and hydrological situation of the site.

In the sequences of planning phase of a TDF (study, approval and planning of the implementation phase) most of the decisions are founded on the results of the subsoil exploration, the site investigation and the geological model as the result of this process. Detailed knowledge of the allocation of aquifers and groundwater stevedores within the planning area, the deformation behaviour of the subsoil depending on petrography and the possibility to improve the sealing and retaining effect of the subsoil are necessary to evaluate the suitability of a site for an installation of a Tailings-Settling-Basin.

In addition exact knowledge of the local geological situation is essential to evaluate and assess the subsoil behaviour of the foundation or surrounding border. Main aspects for estimation site suitability are the geomorphological characterisation and the manner, spread, thickness and geological age of the present stratification of the geological barrier. Further on the tectonic structure of the underlying material, especially genetic construction and responding stress levels, as well as the possible magnitude of earthquake have to be involved into considerations. Deep subsoil lying in sphere of influence, especially if hollows or soluble rocks can be found therein (karst, gypsum-, anhydride- or salt-inclusions) has to be accounted.

1.1.1 Composition and spreading of granular soil

When evaluating the foundation of an impoundment some facts must be known to characterise the existing granular soils in the planning area. For this counts the constitution and stratification of the residual soil covering the rock. When determining attributes of spatial associated soil with probable the same behaviour it is essential to make a conclusion about the constancy as well as the horizontal and vertical spreading of the layers.

In detail the effective pore volume responsible for the permeability of the soil to different fluid mediums such as groundwater and contaminated seepage has to be estimated. Hence in run-up to construction phase an assessment of the probable existing inorganic, organic as well as other pollutants in phase has to be arranged. Furthermore the ability to adsorb and to retard, the durability toward erosion and suffusion and the strain and deformation behaviour of the soil are important criteria.

1.1.2 Composition and spreading of bedrock

Due to the local geological situation and the geomorphologic circumstances the cover of granular soil over the bedrock often can be thin or unfavourable modelled. Therefore the shape of bedrock must be investigated.

In this context the rock has to be explored and categorised as a stratigraphical unit concerning his mineralogical constitution, degree of weathering, resistance to weathering and the type, spacing and orientation of joint faces, as a geological assignment. Particular attention has to be paid to the spreading, the degree of disconnection and the aperture of individual clefts as well as to tectonic and petrographic anisotropies within the rock. Examples therefore are karstification and ground falls.

To evaluate an expectation of intended deformation performance it is important to have comprehensive knowledge of the chemical and physical properties. These are the solubility in groundwater and contaminated seepage, the mechanical strength, the deformation behaviour and the permeability for water, contaminated seepage and gaseous or liquid pollutants in phase.

1.1.3 Hydrogeological situation

Any influence of contaminated water on ground water and especially groundwater extraction facilities caused by leaking from the Tailings-Settling-Basin must be anticipated. To get broad knowledge over groundwater conditions detailed information of seepage gradient and velocity including an indication of long-term and seasonal variations is necessary. The degree of soil ability to adsorb and retard water got an important effect on the mentioned circumstances. Besides rock permeability with minimal and maximal values of transmissivity has to be considered for the relevant subsoil.

Spreading, thickness and depth under surface of the rock and soil should be determined due to their function as a groundwater stevedore or aquifer. Especially intermediated layers with variable attributes could have a function as a horizontal stevedore or drainage. Potentially existing springs have to be localised and specified. When defining ground water layers knowledge of particular heads of perched groundwater and if necessary distance velocity within the and between the particular layers have to be quantified in order to assess the effective pore pressures and seepage forces under and downstream the impoundment.

To guarantee an integrated coverage of the hydrogeological circumstances it is fundamental to analyse the chemical parameters of the groundwater. In particular this is an investigation in terms of geogen pollutants, groundwater hygiene and definition of age. In this context existing zones of water pollution control as well as groundwater extraction facilities and their permanent and temporary effects on groundwater regime have to be observed.

Groundwater is in principle a subject of protection. Therefore even in planning phase of a tailings facility an integrated concept to determine existing and potential occurring pollutions has to be developed. Special attention has to be given to groundwater extraction and their effects on hydro-geological circumstances in planning area. Especially effects of temporary limited, long-term drawdown or rise of groundwater and extraction of groundwater respectively groundwater accumulation in the future leads to variable basic conditions, that will influence both, stability of the impoundment and spreading of pollutants.

Variation of groundwater conditions could happen by natural influences. Effects of neighboured open waters and their changing surfaces as well as their infiltration into the groundwater layers have to be considered. Furthermore it is necessary to have basic information of correlation between precipitation rate and infiltration in groundwater as well as an assessment of the maximum surface run off.

1.1.4 Hydrology and climatic conditions of the site

When investigating in planning state of a Tailings-Settling-Basin hydrological circumstances are very important. The main potential for a pollution of the surrounding environment leads from a transportation of pollutants through run off water and seepage. Factors affecting the water balance are tailings water, precipitation, run-off water, seepage and evaporation. Fluctuations of water balance got a direct influence on the structural stability of the safety elements of the tailings dump. Therefore an identification of the site depending maximum possible impact, precipitation, run-off from upstream area and flood is necessary, as well as their recurrence intervals.

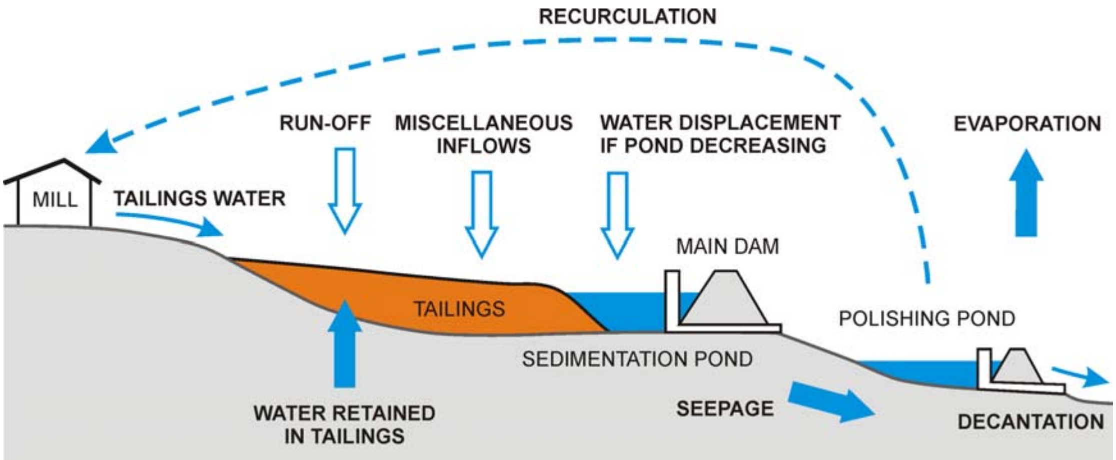

Figure 1: Hydrological cycle of a Tailings Disposal Facility.

1.1.5 Special facts concerning the subsurface

Heavy damage of the natural situation can occur as a result of man-made modifications of the subsoil. The installation of a Tailings-Settling-Basin can collide with existing deposits or raw material and old piles and dumps.

Another task is to check the stability of existing slopes which can be affected by the TDF especially by changes of groundwater conditions. In addition all phenomena of previous or still operating mining had to be considered. This means existing submerge of ground and galleries. The closure of possibly available former galleries (under ground and strip mining) must be checked.

Before constructing the facility subsoil had to be investigated for worth mining materials and available geological and archaeological memorials. In case of using stockpiles or fills an exploration of the deep subsoil is necessary.

As a basic principle before constructing phase the pollution of soil and groundwater has to be detected as conservation of evidence.

1.2 Inventory

Each site is unique in terms of its location, topography, geology and environment. To estimate the general acceptability of a site the following named explorations almost suffice. Perhaps additional trenches, probing and/or borings could be necessary.

An inventory fundamentally consists of a combination of all existing information from geo-scientific and topographic maps, meteorological dates, former project records, aerial and possibly space views (black and white, colour-infra-red and thermal infra-red), site design and use from former anthropological changes as well as water management dates and analysis of existing layer directories of borings. Beside soil-scientific and digging maps provide important advises of the subsoil. Furthermore information could be given by geological and hydro-geological maps.

1.3 Geotechnical Field Investigations

1.3.1 General

The geotechnical exploration of a possible location for a TDF starts with a careful investigation and the planning of an investigation program that contains field and laboratory tests. The definitive complexity of the investigation often results out of the process of investigation.

A direct view on the subsoil is to be guaranteed through borings and trenches, in special cases also through shafts and experimental galleries. Indirect methods like penetration tests and geophysical methods are helpful especially in connection with the investigation of large areas. Borings lead to selective exploration points of the subsoil condition. Anisotropy of the subsoil as result of changing sedimentation conditions require for declaration of natural sealing layers a dense boring grid or longer trenches combined with geophysical measurements.

When exploration points and samplings will be executed and/or when the type of soil and rock will be categorised available standards must be attended. A photographic documentation of core samplings and trenches should complete the investigation.

Investigations of the subsoil have to include the entire planning tailings settlement area and the surrounding area of influence. Because of the resulting hydro-geological situation a possible impact of the groundwater have to be considered. Settlements, as a result of tailings surcharge, must be regarded and have to be considered about the complete exploration depth. Furthermore possibly existing vertical hydraulic connections between higher and lower aquifers should be observed.

The procedure and plan for a subground investigation can be summarized in the following order:

- Assessment of the geotechnical and environmental risk and classification of the safety
- Complete analysing of the project location, that is the current topography of the site
- Mapping and Review of all available pre-existing information
- Development of an initial hypothesis of the geological and geotechnical conditions of the site including type, configuration and mechanical character of the soil and rock
- Derivation of the relevant parameters for design decisions
- Development of a site investigation plan including a physical geotechnical site exploration as well as a geophysical survey
- Monitoring of all measures of investigation and optimisation of the strategy in dependence of the results
- Laboratory tests of samples to characterize the soil/rock and check their mechanical behaviour
- Check and improvement of the prior hypothesis and establishment of a geological soil/rock model of the site including evaluation of the soil parameters, their variability and uncertainty
- Evaluation and assessment of interactions between subsoil and deposit
- Evaluation of the cost-benefit-relation for additional field information to reduce the uncertainty and risk within the geological and hydro-geological model

Investigation program has to be disposed, controlled and analysed by a professional geotechnical expert which also decides about the execution of geophysical investigations as well as drilled hole experiments to define the rock quality. Generally the following methods are used:

1.3.2 Loose soil

To determine soil stratification and mechanical properties of loose soil a number of field investigations are necessary. A basic classification can be conducted in direct and indirect attempts.

Indirect field investigations provide results without real knowing about the soil that is only secondary results (resistances and pressures) could be measured. Such methods are soundings, static and dynamic penetration testing, micro-seismic, water pressure testing and drill hole geophysics as well as geo-electric profile measuring. Micro-seismic especially appropriates to define thickness of layers and to recognise approximate of loosening zones into border range between rock and loose soil. Due to geo-electric methods and drill hole geophysics it is possible to determine spreading and thickness of layering as well as an outlining definition of permeability.

Direct field investigations feature sampling of probes. Thus exist basis for detailed laboratory tests to determine mechanical behaviour of the investigated soil. Direct field investigations are borings with continuous extraction of samples (core drillings), trenches, optical soil penetrometer and shafts and galleries in special cases. Core drilling can be combined with orientation of direction to rearrange the stratification of the cores.

1.3.3 Groundwater condition

With help of exploration drillings which should be extended to observation wells for groundwater measurement, the hydrogeological properties of the planning area can be explored. Position and depth of the observation wells should be selected in a way that different aquifers can be clear identified and probing can take place in all aquifers. To set up an appropriate groundwater model it is necessary to measure single groundwater levels and if necessary to compare chemical analysis of the water.

Measurement of the groundwater levels have to be repeated to recognise variations. In this way it is possible to consider an intervention into groundwater balance due to the Tailings-Sedimentation-Basin.

Groundwater observation wells should be constructed in a way that sampling through underwater pumps is possible. Diameter of the pipes has to be selected in a sufficient size (5 inches) and infiltration of surface water into the station has to be prevented. Field tests can be required to describe permeability and flow conditions. Beside this a net of observation gauges can be used to carry out traces tests.

1.4 Laboratory Investigation

1.4.1 Soil-mechanic and rock-physical tests

For classification and determination of the most relevant physical parameters like strength, stress-deformation-behaviour as well as the permeability of soil and rock laboratory investigations on samples from borings and trenches should be carried out. The variation of single layer characteristics can be derived by a sufficient number of single tests. Type and scale of the investigations have to be fixed by a qualified geotechnical expert. Execution of the investigation has to be documented to safe the inventory and the comprehensibility of the results.

To determine characteristics of the rock an analysis on rock samples concerning grain size distribution (if loose weathered material is available), swelling, permeability of the joint faces and of the porous rock, degree of weathering, resistance to weathering and solubility of the rock in contaminated fluids have to be carried out. Additional investigations must be executed if it is necessary for determining the mechanical behaviour of the rock, filling of rock joints or weathered interlayer.

All tests should be run in accordance to the relevant standards defined in ASTM or EC7 part 2.

1.4.2 Chemical tests

The quality of the groundwater within the different soil layers can be determined by chemical investigations. The amount of investigation has to be fixed by an expert with experience in hydrological investigation. The specification has to take place under consideration of the relevant set of standards and in coordination with a experienced chemical analytical laboratory.

1.5 Description and Evaluation of Examination Results

To evaluate and assess the geological, hydro-geological and mechanical behaviour of the subsoil (soil and rock) a completing report has to be made on the base of the results of the field investigations and the laboratory tests. Aim of the report is the evaluation of site concerning to its planed use and the characterisation of the subsoil conditions respectively parameters. The report should consist of a written and graphical description and the assembling of all data determined.

The results of the site investigation have to be analysed and assessed with respects to the planning state and the demands of the safety conception. Layers have to be classified concerning to their thickness, depth under surface, constancy, permeability, adsorption ability and quality of sealing or retaining capacity. Furthermore the report must contain a groundwater model with basic information about the groundwater characteristics and subsurface permeability for the location of the deposit and the surrounding area. Therefore the overall outcome is the physical geological model which should simplify the situation and conditions in homogeneous zones.

Structural integrity and deformation behaviour of the subsoil have an important influence on long-term stability of the impoundment. In the course of working phase both have to be evaluated. In addition a classification of the earthquake situation and the possible threat through mining subsidence by means of tectonic circumstances is necessary.

According to relevant standards and set of rules graphical illustrations of results with capital importance has to be made. To illustrate investigation results it is advisable to use graphical description and schematic summary especially if these contain huge data material. For graphics the dispose of site plans, sections through subsoil and 3-dimensional representation of the subsoil are eminently appropriate. The mentioned descriptions could be supplemented through spatial mappings and sections in the form of geological sections and block models.

When presenting data in site plans the depth scale chosen must allow identifying thickness relevant for stratification of the subsoil investigations. Thickness of soil layers, existing technical structures, groundwater tables respectively heads of water also have to be noted. For reasons of clearness of data description it is recommendable to plot separate site plans pro themes like spreading of groundwater (permeability and flow direction) and potential of groundwater contamination. Special predestined for a description with in a site plan are details concerning water balance, new entity of groundwater, variations of groundwater tables as well as the influence of floods and tides.

From a global point of view these details contribute to a structural and environmental risk assessment starting from the use of the site to deposit tailings material in the planned manner. Thus the responsible geologist or engineer for data collection and assessment should be involve in the ongoing decisions of the process of design.

2 Specification of the Tailings (J. Engels)

2.1 Tailings Characteristics

2.1.1 Introduction

It is important to understand the properties and characteristics of any materials used in the construction of a tailings impoundment. If inadequate knowledge and unsuitable construction materials are used, then the risk of embankment failure is increased. Impoundments sited in areas of natural hazards and seismic shaking are most vulnerable to failure compared to low hazard areas, simply due to there being additional stress characteristics.

In the last 10 years there has been an increased understanding of soil behaviour to seismic shaking (dynamic events). Both water and tailings impoundments have adapted these principals with tailings facilities introducing additional complexity due to there unique characteristics. Today impoundments are designed and built to be permanently stable structures in areas of high seismic activity, even being built on active faults.

2.1.2 Soil and the mechanical behaviour of tailings

A soil mass consists of solid particles that are separated by spaces or voids. These voids can either be filled with air, water or a mixture of both. If the voids are filled with air the soil mass is dry, whereas if only water is present in the voids the soil mass is said to be saturated. If a mixture of air and water is present then the soil is partially saturated. Figure 2 shows the three degrees of saturation.

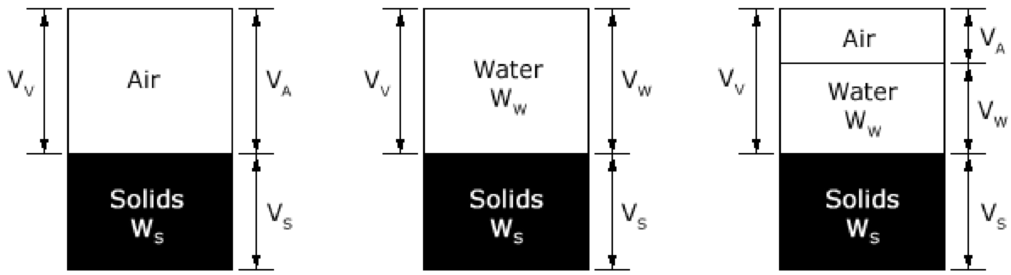

Figure 2: Water and air content in a soil (Smith and Smith 1998).

The following equation is used to calculate the degree of saturation, usually expressed as a percentage.

$$S_r = \frac{\text{Volume of water}}{\text{Volume of voids}} = \frac{V_W}{V_V} \quad (1)$$

Tailings

The properties of tailings are unique to a particular operation. The mineral content, chemical constituents (used in processing), saturation, density, size fraction, plasticity are all the main parameters that influence the behaviour of tailings once deposited in an impoundment. The most vital parameter that influences stability is the saturation. An embankment with a high phreatic line indicates a high level of saturation. Most failures of tailings dams have occurred due to water mismanagement leading to overtopping, face erosion, piping and low freeboard, which all raise the phreatic surface of the embankment.

Tailings or borrow materials are the main resources used to raise the embankment(s) of a tailings dam. Depending on the method of rising (upstream, downstream, and centreline) the properties of the embankment are greatly influenced.

Effective stress

Void ratios decrease in a soil sample when a load is applied, which consequently changes the mechanical properties of the soil mass. This is known as the effective pressure. In a saturated soil stresses exist within the water and solids in all directions, which are the neutral stresses and is equivalent to the pore water pressure. The other stress is a function of the inter-granular pressure between soil particles within a soil mass and is known as the effective pressure. This is represented as:

$$\textit{Effective Stress} = \textit{Total stress} - \textit{Neutral stress} \quad (2)$$

Remembering that for a saturated soil mass the neutral stress is equal to the pore water pressure.

Appling loads to saturated soils causes grain to grain stresses, and increased pore water pressures (as a result of the increased load being partially carried by the water in the voids). For demonstrating the effective stress of a saturated soil mass the soil structure under a load will consolidate with time. The individual grains will compress, but the water content is in-compressible. If drainage is impeded then the load is entirely resisted by the pore water pressure. If drainage is suffice as to allow the water to drain allowing the soil mass to compress then the pore water pressure is dissipated increasing the effective stress and rate of consolidation. For clay soils the drainage rate is usually slow due to the intrinsically low permeability of the soil mass.

Relative density

We know that liquefaction is a common cause of impoundment failure and a crucial factor regarding the susceptibility of a soil is the relative density. This is represented as.

$$D_r = \frac{e_{\max} - e}{e_{\max} - e_{\min}} \quad (3)$$

Under dynamic conditions if a soil is compacted the particles close together and a minimum void ratio is obtained. If the soil is loosely compacted then a maximum value of void ratio is obtained (Smith and Smith 1998). From this equation the highest possible density of a granular soil must occur when $D_r = 1$. Similarly the minimum possible density is $D_r = 0$. Therefore, the higher the relative density the more densely packed the soil, and thus higher stability under dynamic conditions.

Plasticity of fine grain soils

Plasticity describes the ability of a soil mass to undergo unrecoverable deformation at a constant volume without cracking or crumbling. It is a very important characteristic of fine grained soil, indicating that a significant content of clay and/or organic material are present within a soil mass. Depending on the saturation of a soil mass, a soil may exist in liquid, plastic, semi-solid and solid states. Generally most fine grained soils exist naturally in the plastic state (Craig 1997). If there is a decrease in the saturation of a plastic soil then the cation layer decreases resulting in the increase of the net attractive forces between particles in the soil mass. The plastic characteristics of a soil occur when the net attractive forces between particles is such that they are free to slide relative to each other, with cohesion between them being maintained.

For a soil to exhibit plastic behaviour it must have a level of saturation that lies between the liquid limit (w_L) and the plastic limit (w_p). This zone of saturation is known as the plasticity index (I_p), and is represented as:

$$I_p = w_L - w_p \quad (5)$$

The degree of plasticity of the clay fraction known as the *activity* of a soil mass is expressed by the ratio of the plasticity index to the percentage of clay size particles.

Spatial variability

Within a sand/soil mass there are large spatial variability's even within homogeneous zones. It is very difficult to determine this spatial variability and so probabilistic methods are preferred which is nether-the-less cheaper and not subjected to uncertainties as a result of measurement errors. Field tests are the only way to understand spatial variability consequences for particular sites and materials. The Monte Carlo simulation technique is one method used to determine soil properties for specific soil conditions.

Soil liquefaction adds further complexity, as the empty pore spaces become liquefied during seismic shaking, which can only be accounted for by considering the stochastic nature of spatial variability of soil properties (Popescu et al. 1997).

Soil dynamics compared to classic soil mechanics

Dynamic stresses and strains on a soil mass are of a cyclic nature. That is, they undergo several cycles of loading, unloading and reloading. Static forces generally induce monotonic loading, maybe after unloading has occurred. The stress-strain behaviour of a soil mass under cyclic loading is very different than monotonic or near monotonic loading. For example under cyclic loading the stiffness/strength of the soil mass degrades and porewater pressures increase.

Seismic activity provokes deformation of a soil mass rather than load controlled stresses. The seismic load not only induces dynamic cyclic natured stress/strain but also differs in the usual states of stress encountered under static loading. The main tasks for an engineer is to predict and limit horizontally rather than vertical displacement and forces (Banerjee and Butterfield 1987)

2.2 Some Tailings Pollutants

2.2.1 Introduction

Tailings vary in types and concentrations of pollutants. Minerals, chemicals and acidity are the main pollutants that are the foremost concern for the environment. Lesser pollutants (depending on site factors) such as turbidity, temperature, and noise still have to be monitored and managed. Each tailings site has its own characteristics and environmental parameter importance.

2.2.2 Chemical pollutants

The chemicals used in the processing of the mine ore will determine the concentration of certain parameters of the effluent being disposed of with the tailings. For example the BOD, COD, suspended solids, pH, and dissolved solids.

Some toxic chemicals found in tailings include, sulphuric acid, nitric acid, hydrochloric acid, ammonia hydroxide, cyanide, sodium hydroxide, and potassium chloride. These chemicals are generally introduced during the milling stage as frothing, collecting, promoter, and depressant agents.

Acidity (Acid Mine Drainage)

Pyrite bearing ores when disturbed and exposed to oxygen and water form sulphuric acid, ferrous and ferric sulphates. The key parameters affecting the rate of oxidation are the sulphide grain size, the exposed surface area, and the porosity and permeability of the tailings.

$$FeS_2 + 7/2\ O_2 + H_2O \rightarrow 2\ SO_4^{-2} + Fe^{+2} + 2\ H^{+}O \qquad (5)$$

$$2\ Fe^{+2} + 1/2\ O_2 + H^{+} \rightarrow 2\ Fe^{+3} + H_2 \qquad (6)$$

$$2\ Fe^{+3} + 3\ H_2O \rightarrow Fe(OH)_3 + 3\ H^{+} \qquad (7)$$

$$FeS_2 + 15/4\ O_2 + 7/2\ H_2O \rightarrow 2H_2SO_4 + Fe(OH)_3 \qquad (8)$$

From the molecular weights in the equations above, for every 1 kg of pyrite contained in the tailings 1.63 kg of H_2SO_4 would be generated. However, there will be some neutralisation depending on the types of minerals present in the tailings.

Equations (6) and (7) describe the oxidation of ferrous to ferric iron with the subsequent precipitation of ferric hydroxide. This is the red colouring found in acid streams (Ritcey 1989).

Flocculants and Process Agents

Flocculants are used in assisting the rate of settling of tailings slurry. Flocculants are polymers that are either cationic (positively charged), anionic (negatively charged), or non-anionic (electrically neutral). Flocculation by polymers causes bridging between the polymer and two or more particles. This increases density and the bonded particles hinder quicker in the tailings slurry. Metal concentrations in effluent streams can be significantly reduced by flocculation.

Xanthates are the most commonly used sulphide collectors in the mining industry today. They are generally used with pine oil (frother) to help raise the valuable mineral to the overflow of a flotation tank. The underflow is recycled and eventually sent to the tailings impoundment. Only a small amount of Xanthates deposit with the tailings. They generally migrate trough the flotation cells with the product, then eventually decompose in the drying and smelting stages.

2.2.3 Microbiology

Tailings and soils contain bacteria that can influence the organic and inorganic chemical constituents. As with Acid Mine Drainage (AMD) the pyrite and other sulphide minerals are oxidised by the iron oxidising bacteria soluble and insoluble metal sulphates, sulphuric acid and ferric iron. Elemental sulphur can be generated from the oxidation of sulphide minerals from the ferric iron. This can be further oxidised by the sulphur oxidising bacteria to produce sulphuric acid.

The bacteria present in a tailings impoundment is dependent on available nutrients, the temperature, gas and moisture content, and the acidity of the deposit.

2.3 Placement and Adjustment in the Impoundment

Tailings are generally segregated before being disposed of in the impoundment. Typically, cyclones are used to extract the sand fraction from the run of the mill tailings which is used to raise the embankment face. The slimes are deposited via spigots into the impoundment. From these spigots there will also be some segregation. The coarser fraction tends to settle out closer to the spigot and the slimes travelling furthest away generally towards the centre of the impoundment.

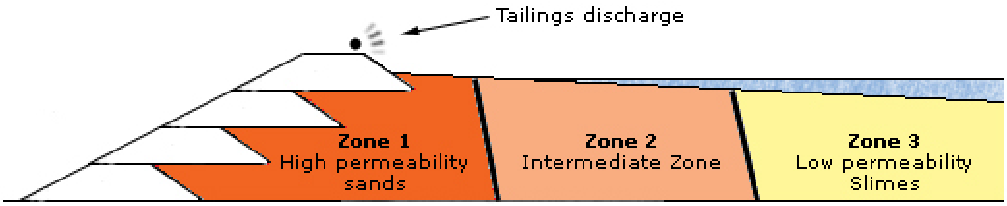

Figure 3: Tailings segregation zones.

The placement of tailings in a conventional impoundment has to be managed so that the free ponded water doesn't become uncontrollable and encroach embankments if the freeboard is low. The Merriespruit and Saaiplaas disasters were triggered from high rainfalls that the decant towers couldn't cope with. The Saaiplass impoundment failed three times in four days. The first embankment failure zone was being raised to push the decant pond towards another area of the paddock as water was causing a high phreatic surface in the embankment.

The slime fraction of the tailings can be introduced for areas of an impoundment that have high permeability zones that are causing seepage problems. The blending will help to lower the permeability of the deposit.

3 Fundamentals of a Good Design (K.J. Witt & R.-B. Wudtke)

3.1 General

The design procedure for a proposed TDF is an ongoing systematic process that takes into account all the relevant factors and criteria to provide an acceptable and known level of reliability for the mine residue deposit. As an overall aim a good design should optimise the three columns i.e. functionality, environmental impact and cost over the entire period from site selection over operation towards closure and aftercare. For any phase of life cycle of a TDF good design results in reports, specific studies, working and as build drawings as well as operating manuals and monitoring requirements. Background studies concern safety classification, risk estimation, environmental impact assessment, characterization of the chemical, physical and structural behaviour of the residues, geological, geotechnical and hydrological assessment of the site, water management, monitoring and auditing.

Usually there are at least three levels of study and design. At the stage of conceptualisation one has to deal with site selection, technical variability of the produced residues, order-of-magnitude cost estimating and preliminary studies concerning potential risks, safety classification and possible environmental impacts. Subsequently the financial variability of the project has to be established in a second stage. Furthermore final engineering decisions and assessment of full environmental impact are required. In the final stage of design detailed engineering and preparation of construction drawings and specifications has to be made for all the basic elements like infrastructure, impoundment, pond, dam, discharge pipeline, recycling system, spillway, seepage collection, drainage systems, instrumentation and monitoring, taking into account the entire life cycle of the deposit. Within the legal and environmental framework the objectives of design in all these stages have a strong bearing on the aspects construction, commissioning, management of operation and finally on decommissioning and closure. Therefore the quality of design is a fundamental criterion for the sustainability of the TDF. Sustainability is satisfied if the intended purpose is fulfilled as expected under all external environmental influences that are reasonable likely to occur.

Design should be undertaken by suitably qualified persons. The level of qualification and experience required depends on the safety classification of the TDF concerned. Another important factor influencing the success of the process is an adequate continuity of communication of the personnel involved in investigation, design, construction and commissioning. In any case depending on the classification of safety of the TDF and the complexity of the task, design as well as construction should be supervised and reviewed by the judgement of independent experts.

3.2 Objectives of Design

3.2.1 Conceptualisation

The life cycle of a TDF and therefore design starts with the conceptualisation and ends with closure and aftercare. The first planning phase is an optimisation of both, production of residues and site selection for the disposal. A wide range of viable alternatives, different ways of pre-treatment, transport and disposal techniques should be examined before a commitment is made to follow a particular option. The result of this phase is a conceptual report for the entire life of the TDF, which should describe all assumptions, parameters and alternatives considered from a legal, technical, environmental and economical view as well as the justification and reason for the final selection.

3.2.2 Safety classification

Even during the stage of conceptualisation of a new TDF and integrated with the preliminary site selection the proposed project should be classified into a safety category defining the potential of possible hazard. An update or reclassification should be made during the development of design and during further milestones of life cycle. Some actual guidelines and manuals give suggestions or schemes for classification and there is an assent that the reasonable likely adverse impact to human beings and to nature should be the main criterion to classify a proposed project in one of the categories low, middle or high hazard. Following the source-pathway-target framework this assessment should take into consideration three aspects, the amount and level of toxicity of the tailings, the ability of spreading and emission by wind, water and groundwater, and the use of the zone of influence. Beside this, socio-economical aspects should be taken into consideration. This qualitative safety assessment shall be extended to a quantitative risk analysis for all deposits with high hazard.

3.2.3 Design requirements

The detailed planning of the site, the infrastructure, the structure of the impoundment, the procedure of deposit, the cycle and management of water and the drainage system is the central part of design. The overall aim is to provide tailings deposition that guarantees functionality, reliability and sustainability and at the same time one should be able to define all operational procedures to reach this aim. The outcomes of a proper design therefore are reports, manuals and drawings that incorporate the requirements:

- Concept and description of constructions, operation and maintenance,
- Specification for constructions, materials and products,
- Qualification and experience of personnel for construction and operation,
- Quality assurance measures,
- Specification of monitoring, reporting and auditing.

Design methods and criteria should be conforming to the current state-of-the-art knowledge as well as to good practice guidelines and standards. The minimum requirements for this process have to be established before beginning. Depending on the complexity of the task and the environmental factors like the character of tailings and leachate, importance and vulnerability of the environment that might be threatened by adverse effects of the deposit. According to the expected frequencies of circumstances and impacts that could possibly occur during life cycle, design situations should distinguish persistent (normal operating), transient (temporarily) and accidental/seismic (exceptional) conditions.

As a basis of design particular background studies are necessary such as:

- Site selection report,
- Environmental assessment report,
- Geometric data like topography and slopes of both, original surface and different stages of the deposit,
- Geological profiles and groundwater levels of the site with focus on the mechanical and hydraulic behaviour of the subsoil i.e. stability and drainage conditions. This description should take into account possible differences between the actual properties as investigated and the predicted future changes due to overburden pressure of the deposit.
- Chemical / biological characterisation of the tailings including conditions for emission and transport of contaminants,
- Mechanical characterization of the tailings including ability of segregation, sedimentation, consolidation, drainage, liquefaction and erosion by wind and water,
- Climate and hydrology of the site, normal and extreme conditions.
- Maximum possible exceptional impacts from natural hazards like earthquake, precipitation, flood and storm as well as definition of the acceptable recurrence intervals (usually 100 - year).

3.2.4 Design verification

Naturally design is verified by calculations. This standard method may be good practice in situations when limit state conditions and data are available and the mathematical model describes adequately the behaviour of the tailings, the subsoil and/or the water. When comparable experience is available prescriptive measures are allowed without detailed calculation. Such measures should involve conservative details, specifications, materials or operational procedures. If there are real gabs in science and knowledge about the mechanical properties, effects of time or scale, so that even a sufficient prediction is not possible, experimental models and large-scale tests should be carried out to observe and accurate determinate the relevant parameters. Under all circumstances, where design cannot be verified by experience, serious calculation, numeric modelling or field test, the method of observation is an adequate method to review design during the operation of a TDF. Nevertheless this approach needs an estimation of the possible behaviour, a prior establishment of limits of behaviour or threshold values as well as a strategy how to decide, when the behaviour is outside the acceptable range.

One of the fundamental rules to reach a good design is to achieve robust and reliable constructions. This can be assured by avoiding, eliminating or reducing possible risks. In detail the level of reliability will rise by selecting design details and structural shapes with low sensitivity to the impacts, that might be present, and by constructions that will have a high tolerance to the manifestation of risks. Therefore operation and maintenance conditions should be as simple as possible. Furthermore design has to be flexible to guarantee the possibility of adjustment under changing external circumstances.

3.2.5 Reports and drawings

The outcome of the design procedure, report and drawings, should include as a minimum the following information:

- Resolution of all parameters and assumptions on which the classification of the safety is based,
- Aims and constraints of operation, description and design,
- Engineering drawings showing the general arrangement of the site before deposition,
- Engineering drawings showing the different stages of the deposition including the arrangement of the impoundment and the associated infrastructure for water management,
- Engineering drawings showing structural details of the impoundment, dam or outer perimeter dyke, including sizes, drainage systems requirements on slope, allowable grain sizes, compaction and freeboard,
- Resolution of the closest acceptable distance of the pool from the outer dyke at different stages of rise,
- Engineering drawings showing the borderlines and the extension of the dam, the lagoon and the pond for different stages of deposition,
- Engineering drawings and calculations showing all measures for flood prevention like dams, galleries and spillways,
- Engineering drawings of design details and description of all measures for preparing the site for deposition such as initial earthworks, decanting systems, liners under drainage and other measures for pollution control,
- Classification of the tailings material including assessment of production rates, transport and build in conditions,
- Drawings and definitions for distributing the tailings material in order to achieve the required geometric shape and the structural integrity of the deposit,
- Calculation and prediction of dewatering, settlement and water balance changes within the deposit,
- Calculations for structural and hydraulic adequacy in consideration of safety factors, slope stability under different design situations, erosion and bearing capacity,
- Specification and description of the location for an all-embracing monitoring including data transfer, frequency of measurements, reporting and procedures recording.
- Emergency plan defining technical identification of emergency, adequate measures the areas threatened, emergency warnings, communication and warning systems and the emergency decision-making process.

3.2.6 Structural safety analysis

With respect to the structural safety and reliability design, construction, decommission, and maintenance of the outer dam or perimeter dyke is one of the most risk relevant tasks. The dam and the appurtenant works must be designed to withstand the most severe and unfavourable combination of static, dynamic and hydraulic impacts. This includes also events occurring during the long period of construction. The amount and extent of foundation exploration should be appropriate to the size and importance of the structure and to the complexity of the local tectonic and geologic features. The detailed requirements are reported in chapter 4.1.1 “Fundamentals of site investigation”.

Another very important aspect of structural safety is the control of seepage, phreatic surface and pore pressure. These parameters have a strong bearing on the overall stability of the downstream slopes and influence the internal erosion, piping as well as pollution of ground and surface water downstream the dam.

Stability analysis of the impoundment and especially for the outer slope should be undertaken for the different situations of progress. This analysis must consider all possible design situations including earthquake, unexpected deformations, various conditions of phreatic surface under anisotropic conditions, pore pressure within the dam and the foundation. Potential failure surfaces can have a variety of geometric shapes. For non-homogeneous or layered conditions within the dam and the ground, multi wedged analysis with contrasting shear strengths will be required. Finite element analysis for stability and seepage development should be based on simple reliable models and on parameters verified by measurements or best predictions. With regard to the possible accuracy and to the spatial variation of the data the purpose of numeric modelling should be to gain a better understanding and to assess alternatives, rather than to create quantitative predictions.

3.2.7 Hydrology and hydraulics

Tailings water stored behind the dam is usually toxic. Therefore no discharge of effluents into environment is allowed. The pond water balance becomes a critically important factor because all inflowing water to the sedimentation pond must be stored and treated before releasing the facility area. Normal losses of seepage, which are overall acceptable for a conventional water storage dam, could be unacceptable for a tailings dam due to the contaminants contained in the seepage water.

Before starting the design work a basic definition of the criteria, upon hydrologic and hydraulic circumstances, has to be made. This includes a documentation of the defined criteria. When defining the availability of processing methods and equipment, the degree of precision of computational methods and the possibility of substantial modification in drainage area should be involved.

The design of tailings dams must be based on the probable maximum impacts like rainfall, pore water pressure and flood (PMF). Accuracy and reliability of hydrological data derived from historical records can be checked by theoretical computation. For validation and improvement of data precipitation records and runoff data from neighbouring drainage areas may be applied.

3.2.8 Instrumentation and Monitoring

Instrumentation and monitoring is to integrate in the planning phase and should be adapted and progressed in the stages of construction, operation, decommission, closure and after-care. In any phase the overall aim is to provide data, which are relevant for the decisions during the ongoing management, procedure of design and safety assessment. Therefore monitoring can be focused with respect to potentially significant impacts, structural safety assessment, water management, deformations, climatic conditions, pollution control, any effects of deterioration or to long term changes in environmental conditions. The operating manual therefore should include a detailed description of both, the required data and the methods to get them. A detailed monitoring plan should define the aims, the parameters measured, the possible technique and frequency, the responsibility, the reporting and dissemination as well as the conditions under which monitoring should be extended or could be stopped. The specifications for visual inspections are part of this monitoring plan. One of the essential tasks of monitoring is a prior resolution of threshold values and acceptable limits as well as an adequate strategy how to manage conditions beyond the acceptable range.

3.2.9 Closure and aftercare

A long term or after use plan (rehabilitation plan) is becoming increasingly common for licensing or regulatory agencies and meets the requirement of sustainability. This process of planning should be prepared as part of environmental statement accompanying the initial planning submission. Rehabilitation of a tailings facility is a site-specific problem, which depends particularly on the physical behaviour of the site, the layout of the deposit and the nature of the stored tailings. The physical behaviour can be characterized by topography, size of watershed, climatic conditions, geotechnical properties and seismic conditions of the effected area.

To achieve maximum effectiveness and economy this last but longest stage of life cycle should be considered still at initial phases of the planning. This also permits a development of tailings handling facilities that are more suitable to rehabilitation at the end of a mining operation. Such a plan should include a detailed description of the current state of the surrounding dam and the pond, a stage-by-stage outline to convert the current tailings dam and pond into rehabilitation condition and results of measurements to define the degree of contaminants eroding from the site. The final rehabilitation plan should address extreme climatic events as well as long term relating processes like changes in environmental conditions due to unavoidable pollutions and impacts under different options of land use. Beside these technical aspects cost estimates for the works and operational resources as well as all the residual environmental impacts should be under consideration. The plan should provide sufficient details and flexibility to facilitate its implementation and should be developed in consultation with all the affected parties who will assume responsibility for aftercare.

4 Management and Review (K.J. Witt & R.-B. Wudtke)

In context with the life cycle of a tailings deposit facility (TDF) all marginal decisions in every phase have to be verified independently reviewed to guarantee a smooth function of the facility. Figure 1 gives an overview of the sequences of development from site selection towards aftercare.

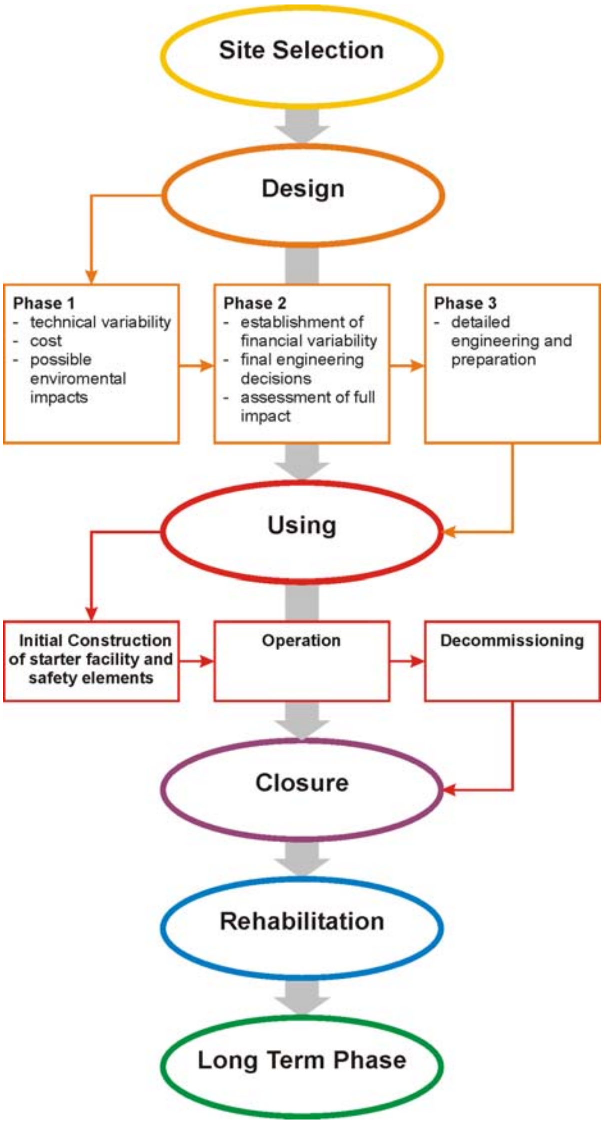

Figure 4: Sequences of the life cycle of a Tailings Deposit Facility.

Depending on the strain of the safety elements and the total potential of a possible contamination of environment the main focus to define marginal conditions of necessary investigations has to be specified particularly. The plausibility of the definitions has to be checked in every single case by an external expert.

To reach the goal of an effective prevention of mistakes an independent review and assessment of a tailings facility is unavoidable. A problem depending delegation of fields of responsibility to common experts is advisable. Management system, risk assessment, emergency preparedness and response, water management, physical and chemical stability, migration of contaminants, surveillance while operation, slurry and recycle pipelines, closure planning, signing off procedures and finally verification processes are exemplified in context with an tailings facility important fields of responsibility and should be advised by suitably qualified independent senior experts.

A central basis to analyse the dam stability, the predefinition of the degree of contamination over air and water and the functionality of the safety systems are measurements as a result of the monitoring. The decision over type and complexity of the measuring systems involved into the monitoring has to be made on basis of the existing local geological, hydro geological and topographical conditions of the area. Furthermore the static and hydraulic influence of the superimposed tailings and its effects on the environment and the ground water has to be considered.

An emergency plan has to be established for all life phases of a TDF. It must be updated depending on the changing marginal conditions over the life cycle. In any case of a hazard it has to be possible to revert to an appropriated decision plan, which guarantees short-term reactions and retaliatory actions. Population density within the potential affected area, impact on ground water quality, air pollution, changing topography caused by operational manipulations, influence on direction of ground water flow and soil conditions, stability and functionality of drains and other safety systems are marginal conditions in this context.

A broadly compilation of questions appearing during the sequences of development as well as their dependence on the particular actions are listed in Table 1. In general this is for every part of use a basis for decisions made by a panel of expert. All these actions can be summarized as process of planning, that should take cognisance of full cycle implications and should include technical and socio economical aspects within the legal framework. A proactive and structured management of the processes of planning, construction, operation and closure is central to technical and economical success. As an appropriate management framework the model of ISO 14000 system, developed for environmental management, can be established. The essential components are policy making, setting of objectives, operation, conformance assessment, management review and ongoing improvement. A suitable illustration and detailed demands according to TDF are given in the South African Standard Code of practice “Mine residue”. In any case, every successful management system has the components documentation and records, definition of responsibilities, qualification of personnel, review by independent experts and regular auditing. This of course, is the most powerful tool influencing the adequacy and effectiveness and therefore the safety and reliability of a TDF during the life cycle.

Table 1: Description of the phases concerning actions monitored by external experts (ICOLD 1989).

Phases	Groundwork	Actions
Design	- probable tailings volume - site investigation - morphology and infrastructure of the area - type and behaviour of tailings - geological and hydro-geological situation	- design of the safety systems - design of a monitoring - definition of an accident plan
Installation	- protection of built components - necessary minimal dimensions - simple and proof constructions - climatic conditions - availability of used construction material	- installation of sealing control systems - building of basis dam - installation of a monitoring - installation of an accident plan
Use	- continuous evaluation of measurements (monitoring) - comparison: prognosticated tailings volume vs. actual tailings volume	- estimate of dam stability - adaptation of the monitoring - adaptation of the accident plan - decision: achieving of maximum dump capacity
Closure - Rehabilitation	- description: current state of surrounding dam and pond - results of measurements: definition of contaminants eroding from the dump (air, water)	- design of a rehabilitation plan - design and construction of safety systems (include existing systems) - adaptation of the monitoring relating to long term phase
Long term	- continuous evaluation of measurements (monitoring)	- provide accident plan

5 Literature

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