Chapter 11

Disposal of Residues

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11.1 Aim and Scope

No metallurgical textbook would be complete without a chapter dealing with residue disposal. In this chapter an overview is given of the aspects which require consideration when planning, operating or closing a tailings dam; it should therefore provide background knowledge for the effective management of tailings dams. Emphasis has been placed on those aspects which require investigation by specially qualified personnel. In this regard the extent and nature of the requisite investigations have been discussed and the minimum qualifications of those undertaking the work have been given.

The bulk of this chapter concentrates on surface disposal, since at the time of writing underground stope backfilling had only been carried out on a pilot scale on South African gold mines. It is however recognised that the volume of tailings sent underground will probably increase and that the remaining fraction will become finer and more difficult to manage.

It is of particular interest to note that the responsibility for safe and effective disposal of the tailings underground no longer falls to the discipline of metallurgy. The overflow or surplus will, however, always be disposed of on surface, and this is likely to remain within the metallurgical scope.

Particular aspects of surface disposal of residue covered in this chapter include:

- sizing, siting, designing and operating gold tailings dams;
- legal and environmental regulations governing the establishment, operation and closure of a tailings dam;
- some operational “do’s and don’ts”;
- observation and control of the tailings disposal operation;
- present state of the art in closure and rehabilitation of gold tailings dams.

The chapter has been confined to hydraulically placed gold tailings impoundments. Dumps have not been covered, since, in terms of potential for generating problems, tailing dams have a much more significant history of operational, environmental and safety problems, they are generally poorly understood, and require considerably more attention.
11.2 Planning

11.2.1 Components of a residue disposal system

By way of introduction to this section on planning a surface tailings disposal scheme, it is useful to list the various components of a tailings disposal complex and briefly describe their purpose. Consideration of each of the com-
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ponents during the siting, sizing and investigation of potential impoundment sites is important in view of their influence on cost, area provision and future operation.

- Containment wall or toewall — a wall, usually of compacted earth, to contain the tailings either as a total confining structure or during the early development of the impoundment.
- Underdrainage system — a system of filter drains to control seepage within the impoundment.
- Decant system — a pipe system to facilitate the removal of clarified water and stormwater accumulated on the impoundment.
- Delivery system — pipework, valves and discharge points to convey the pulp to, around and into the impoundment.
- Return water system — a system of dams, sumps, pumps and pipelines for holding and conveying excess effluent and stormwater from the tailings dam to the plant.
- Stormwater diversion system — a system of trenches and bunds constructed around an impoundment to control and divert external stormwater around the impoundment.
- Stormwater catchment paddocks — a system of paddocks constructed around the toe of the impoundment to capture, control and store stormwater and sediment eroded from the side slopes of the impoundment.
- Ancillary system — comprising access roads, power supply system, etc.

These components are illustrated in Figure 11.1, which depicts a plan layout of a typical gold tailings dam.

11.2.2 Sizing

11.2.2.1 Depositional area requirements

The first step in planning and providing for tailings disposal is the definition of the required area of ground which will meet the constraints of total volumetric capacity required for a manageable height of dam and rate of rise or operating cycle time. At this stage of planning, a maximum height of 35 - 40 m would be assumed and a rate of rise selected on the basis of pulp density and anticipated foundation soils. Figure 11.2, as proposed by Wates (1983), serves as a guide.

Typically, gold tailings have a settled density in a tailings dam of between 1250 and 1650 kg/m$^3$ depending on the depth of tailings. A reasonable figure to assume for sizing calculations is 1450 kg/m$^3$. The required tailings dam area can then be calculated very simply from the equation:

$$\text{Area, m}^2 = \frac{(\text{t.p.m.} \times 12)}{(1,45 \times \text{ROR})}$$ (11.1)

where t.p.m. = dry tons deposited per month, and ROR = allowable rate of rise (m/yr).

This area takes no account of ground topography, or of reduction of area as the dam grows. Figure 11.3 gives an indication of factors which could be applied to the depositional area of approximately square dams on sites with a significant ground slope.
The actual rate of rise on a sloping site will tend initially to be above the calculated figure and thereafter will decrease to just above this figure when all ground is covered. From this stage the rate of rise will begin to increase again due to the reducing area as the side slopes of the dam are formed.

In the case of paddock dams, at rates of rise above the limits implied by Figure 11.2, cycle times between lifts become too short to allow sufficient drying and desiccation of each lift. Access becomes difficult and, while rates of rise in excess of 2.5 m/yr can be tolerated for limited periods of time, above a height of 2.5 to 5 m, stability problems will eventually result.
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Area required = Area × multiplying factor

Figure 11.3. Correction to dam area for various ground slopes.

The anticipated period of usage of the site may be calculated from:

\[
\text{Time (years)} = \left( \frac{h_{\text{max}} \times 1.45 \times \text{(area)}}{\text{t.p.m.}} \right) \times 12 \quad (11.2)
\]

- \(h_{\text{max}}\) = maximum height, m
- area = average area, m²
- t.p.m. = dry tons deposited per month.

At this level of planning, a maximum height of 35 m would be a reasonable assumption. Detailed design and the provision of suitably positioned drainage media could facilitate an increase in this height to 50 m and more, provided rate of rise constraints are not exceeded. If the period of usage of the site from the above calculations proves inadequate it is advisable to reverse the calculation to give the depositional area required to attain a height of 35 m. This will also result in a lower average rate of rise.

11.2.2 Allowances for services
To the above areas should be added a perimeter of sufficient width to allow for the formation of:
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- a stormwater cut-off trench (4 – 7 m);
- an access road (5 m);
- a delivery/return water pipe servitude (2 m);
- the solution trench (4 – 7 m);
- catchment paddocks (20 m).

Allowing for earthwall widths, a perimeter width of 50 m is common. The area implications of this perimeter depend on the plan shape of the dam, which will define the perimeter length. For a square dam of area \( A \) the service area (SA) would be reasonably approximated by:

\[
SA = 200 (50 + A^{0.3}) \text{m}^2 \quad \text{for } A \text{ in } \text{m}^2
\]

### 11.2.2.3 Return water system

Allowance should be made at this stage for a return water system. In some cases, however, no return water can be accepted and it is necessary either to treat the water to meet metallurgical or stream standards, or to provide for evaporation of the excess water. In the case of evaporation, the required areas can equal or exceed tailings dam areas and will require specific planning outside the scope of this chapter.

In most cases a water dam, pumps and pipeline are provided with sufficient capacity to capture and control rainfall under specified conditions. The area occupied will be dependent on topography and soil cover, but in this initial planning stage it is reasonable to assume that an area equivalent to 25\% of the tailings dam area should be allowed.

### 11.2.2.4 Total area

A provisional estimate of the area of dam required will be the sum of:

- depositional area whether dictated by rate of rise or by capacity constraints;
- the area of services;
- the area of the return water system.

### 11.2.3 Site selection

The area and volume calculations in Section 11.2.1 provide a first indication of the size of the site required. Using this information and a regional topocadastral map, it is possible to identify a region of interest within which candidate sites can be located. This exercise is referred to as "regional screening" and facilitates the elimination of areas obviously unsuitable owing to the following factors:

- too far from metallurgical plant;
- topography too steep;
- access too difficult;
- catchment area too large;
- unsuitable geology or mineralisation;
- ground water discharge area;
- important land use zones;
- sensitive ecological areas.
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Within the areas remaining after the above elimination process, a number of possible impoundment sites may be identified. For each of these the following characteristics should be listed:

- capacity;
- toe wall height (based on a maximum rate of rise of 2.5 m/yr);
- distance from the plant;
- land use constraints;
- other salient characteristics that might affect tailings disposal.

A "fatal flaw" analysis will eliminate sites flawed by characteristics sufficiently unfavourable or severe to preclude use of the site. Table 11.1 provides a list of possible flaws.

Table 11.1. Criteria for fatal flaw screening.

Visual
1. Unacceptable visual impact

Land use/ecological
1. Mineralisation (economic)
2. Man-made features, e.g. pipelines, power lines, major roads
3. Actual or potential urban areas
4. Land with high agricultural potential
5. Historic and archaeological sites
6. Important recreation areas
7. Sensitive or unique ecosystems, wild life or fish habitat, endangered species

Airborne release
1. Dust/erosion – high wind exposure
2. Proximity to human habitation

Seepage release
1. Foundation
2. Discharge to ground water area
3. Discharge to streams
4. Flood plain

Stability
1. Topography (too steep)
2. Faults (active)
3. Foundation conditions (poor)

Operational
1. Capacity (too small)
2. Access (too difficult)
3. Technical feasibility (not implementable)

Cost
1. Development cost (uneconomic project)
Sites not eliminated in the fatal flaw analysis should be visited and data gathered about factors such as: visibility, land use, meteorology/climate, hydrology, geology, soils, vegetation, and ground water.

A conceptual design for each site should be formulated from which an estimate of costs for land, construction, operation and closure should be made and tabulated.

A qualitative evaluation and ranking of the sites subjectively into very good, good, moderate, poor and very poor, on the basis of site selection elements such as those given in Table 11.1, can prove useful at this stage in deciding on those sites to be put forward for detailed investigation. A minimum of two and preferably three sites should be selected for detailed analysis. Detailed investigation may involve drilling if the geology and ground water conditions are of particular concern, as would be the case in dolomites. Further costing and environmental studies and impact analysis would be carried out to define more accurately the implications of using each of the sites.

Semi-quantitative evaluation and ranking procedures are available; they are set out in detail in the paper by Caldwell and Robertson (1983). In the course of these procedures, numbers are assigned to the subjective ratings, categorised in terms of importance and then weighted. These procedures may be called for in cases where site selection is particularly sensitive, and various parties such as government and local authorities, boards of directors, hostile property owners and environmental action groups require a referable, less subjective system for justifying the selection of a particular site. In most cases cost will predicate a site and the subjective analysis will be adequate.

11.2.4 Site exploration

The potential sites from the selection exercise in Section 11.2.3 above should be explored in detail by registered and experienced geotechnical engineers and/or engineering geologists who specialise in investigations of this nature. A soil and drainage report should be produced, and only on the basis of the findings in this report should a final decision on the suitability of the site be taken.

The principal aims of a soil and drainage investigation are to:

- identify and characterise areas of potential foundation problems;
- determine ground water seepage models;
- locate possible construction materials.

The soil and drainage survey should establish the different types of soil horizons covering the site, and their boundaries. The following data should be gathered:

- typical soil profiles, depths to bed rock, the position of the ground water table, preliminary estimates of the permeability of the soils and bedrock, \textit{in situ} shear strengths, and consolidation data;
- indications of the presence of dykes, faults, sills and other geological features;
- the presence of collapsing sands, cavernous dolomites, soft, active or dispersive clays, etc.
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The soil survey will often include deep drilling into the regional water table and the installation of sampling piezometers to establish regional and near surface ground water quality. These data would form background water quality data against which changes can be measured once the tailings dam is put into operation.

Trial holes in the surface soils are excavated using either a large diameter auger or a backhoe, depending on soil depths, and, from these holes, disturbed and undisturbed samples of the soils are recovered. Since trial holes give data on soil conditions at specific points only, in certain cases it may be necessary to use geophysical methods such as gravimetric surveys, microseismic surveys and resistivity surveys to locate sinkhole areas, depths to bed rock and water table depths respectively. The actual siting, distribution and number of holes and the extent of geophysical testing will be decided by the geotechnical engineer or engineering geologist on the basis of the anticipated characteristics of a particular site. Generally, since the slopes of walls of residue deposits are critical in the design, exploration holes will tend to be around the perimeter of the tailings dam.

During the site investigation an appraisal of materials suitable for the construction of earthwalls and filter drains should also be undertaken. This involves the determination of compaction characteristics and the gradings of available sands and gravels.

11.2.5 Pollution control considerations

By virtue of their size, poor ability to resist wind and water erosion and the hydraulic fill method of construction, tailings dams can, if adequate provision is not made to control these factors, pose serious long term pollution problems.

Around many of the gold mines on the Witwatersrand and elsewhere, sizeable communities have evolved to serve the peripheral industries required by these mines. Often housing development encroaches on the mine property boundary. Consequently the extent and nature of the potential pollution hazards have increasingly become factors which can influence the choice of a particular site.

In the course of the site evaluation, if the factors given in Section 11.2.3 are taken into consideration, the predominant wind directions and meteorological characteristics of the mine will have been determined. Also, the soil exploration exercise in Section 11.2.4 will give data from which the potential for ground water contamination through uncontrolled seepage under the dam can be assessed. These characteristics of the site fall within the orbit of certain legislation (see Section 11.3). In planning a site for a new tailings dam, therefore, particular attention must be given to pollution control considerations. Remedy of pollution problems, particularly ground water pollution, once these have begun, can be costly, with only limited prospects of complete success.
Table 11.2. Legislation affecting tailings dams.

<table>
<thead>
<tr>
<th>Act</th>
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<tbody>
<tr>
<td>Act</td>
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<tr>
<td>Aspects covered</td>
</tr>
<tr>
<td>Relevant sections</td>
</tr>
<tr>
<td>Controlling body</td>
</tr>
<tr>
<td>All actions directed at or liable to have an influence on the environment</td>
</tr>
<tr>
<td>Section 24</td>
</tr>
<tr>
<td>Dept. Environment Affairs</td>
</tr>
<tr>
<td>Water Act No. 54 of 1956, as amended</td>
</tr>
<tr>
<td>Safety of dams, treatment and disposal of effluents, water use and entitlements, surface water management, water pollution control, water care works, disposal of underground water, effluent water quality</td>
</tr>
<tr>
<td>Sections 9, 11, 12, 12A, 20, 21, 22, 23, 24, 30 and Regulations No. 287 of 20 February 1976, R991 of 18 May 1984 &amp; R2834 of 27 December 1985 as amended in toto</td>
</tr>
<tr>
<td>Dept. Water Affairs</td>
</tr>
<tr>
<td>Health Act No. 63 of 1977</td>
</tr>
<tr>
<td>Air pollution control; water pollution control</td>
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<tr>
<td>In toto</td>
</tr>
<tr>
<td>Dept. Health and Welfare</td>
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<tr>
<td>Atmospheric Pollution Prevention Act No. 45 of 1965</td>
</tr>
<tr>
<td>Dust control</td>
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<tr>
<td>Sections 27 and 28</td>
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<tr>
<td>Dept. Health and Welfare</td>
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<tr>
<td>Soil Conservation Act No. 76 of 1969</td>
</tr>
<tr>
<td>Soil erosion control</td>
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<td>2,3.(k) and 3 (m)</td>
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<tr>
<td>Dept. Agriculture</td>
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<tr>
<td>Conservation of Agricultural Resources Act No. 43 of 1983</td>
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<tr>
<td>Maintenance of production potential of land, combating and prevention of erosion and weakening or destruction of water sources, protection of vegetation, combating of weeds and invader plants</td>
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<tr>
<td>In toto</td>
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<tr>
<td>Dept. Agriculture</td>
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<tr>
<td>Physical Planning Act No. 88 of 1967</td>
</tr>
<tr>
<td>Zoning and use of land for industrial purposes, quarry development and rehabilitation</td>
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<tr>
<td>Sections 2, 4, 6B and 8</td>
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<tr>
<td>Dept. Environment Affairs</td>
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<tr>
<td>Dept. Mineral and Energy Affairs</td>
</tr>
<tr>
<td>Weeds Act No. 42 of 1937</td>
</tr>
<tr>
<td>Control of weeds and pest plants</td>
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<tr>
<td>In toto</td>
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<tr>
<td>Dept. Agriculture</td>
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<tr>
<td>Agricultural Pests Act No. 36 of 1983</td>
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<tr>
<td>Prevention and combating of agricultural pests</td>
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<td>In toto</td>
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<td>Dept. Agriculture</td>
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</tbody>
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<table>
<thead>
<tr>
<th>Act</th>
<th>Aspects covered</th>
<th>Relevant sections</th>
<th>Controlling body</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nuclear Energy Act No. 92 of 1982</td>
<td>Control over radioactive wastes</td>
<td>Section 5.1</td>
<td>Dept. Mineral and Energy Affairs</td>
</tr>
<tr>
<td>Hazardous Substances Act No. 15 of 1973</td>
<td>Control of transport, dumping, storage or disposal of any hazardous waste, including radioactive material</td>
<td>Sections 2, 3 and 29</td>
<td>Dept. Health and Welfare</td>
</tr>
<tr>
<td>Mines and Works Act No. 27 of 1956</td>
<td>Regulations concerning protection of public safety, environmental protection, rehabilitation plans, removal of topsoil, stream and river diversion, waste disposal, re-vegetation, storm water and effluent control and disposal</td>
<td>Section 12 and regulations 2.10, 5.9, 5.10, 5.12, 5.13 and 5.14</td>
<td>Dept. Mineral and Energy Affairs</td>
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<td>Dept. Water Affairs</td>
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11.3 Statutory Requirements

11.3.1 Legal considerations

Environmental control legislation in South Africa is widely fragmented among numerous Acts of Parliament which bedevils the systematic integration of environmental planning into the design of mines and associated activities. The environmental aspects which are, to some extent, provided for in existing legislation are: water use and disposal, water pollution, air pollution, soil conservation, conservation of vegetation, rehabilitation, and dam stability and safety.

Existing legislation which provides for environmental control is listed in Table 11.2.

The main Acts controlling the design, construction and operation of a gold residue disposal facility are the Mines and Works Act (Act 27 of 1956) and the Water Act (Act 54 of 1956) as amended from time to time. Relevant aspects of these Acts are discussed below.

11.3.1.1 The Water Act

Although many sections of the Water Act are applicable to gold residue disposal, the most pertinent provisions can be summarised as:

- safety of dams (Section 9B and 9C);
- use of public water (Sections 11 and 12);
- alteration of water course (Section 20);
- disposal of effluents (Section 21);
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- prevention of water pollution (Section 22);
- pollution of water to be an offence (Section 23);
- right of access of inspectors (Section 24);
- regulations relating to the prevention of the pollution of water (Section 26);
- penalties and fines for non-compliance (Section 170);
- award of damages (Section 171).

Regulations in terms of the Water Act of 1956 which are currently in effect and of relevance to tailings disposal systems are:

- R287 of 20 February 1976, which deals with the prevention of water pollution;
- R991 of 18 May 1984, which sets out quality criteria for waste water, effluent and seepage in terms of the General Standard and Special Standard.

11.3.1.2 The Mines and Works Act

Environmental regulations have been made in terms of Section 12 of the Mines and Works Act. These regulations were promulgated under Government Notice R992 of 26 June 1970 and R537 of 21 March 1980. Provisions which are pertinent to gold residue disposal are listed below:

- rehabilitation of dumps (Sections 5.10 and 5.13.2);
- waste disposal (Sections 5.13.1 and 5.13.4);
- location of dumps adjacent to watercourses (Section 5.14.3);
- poisonous water (Sections 5.9.1 and 5.9.2).

11.3.2 Licensing

At the present time no licence or permit is required to operate a gold residue disposal facility as such. Generally, however, all mines will need to make applications for the following permits, which involve matters concerning slimes dams:

Department of Minerals and Energy Affairs:
Application for a permit in terms of Section 8(1)(a) read with Section 6B/4(2) of the Physical Planning Act (Act 88 of 1967).

Department of Water Affairs:
Application for permits/exemptions/registrations in terms of Sections 12, 21 and 30(5) of the Water Act (Act 54 of 1956 as amended). These applications are made on what is known as the M2 Questionnaire and pertain to the use, treatment and disposal of water at a mine.

11.3.3 Environmental impact assessment

By placing some emphasis on environmental planning, a mine will realise a number of benefits:

- a good public image;
- compliance with legislation;

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- the preservation of the environment, if not actual environmental improvement;
- proof that industrial development can go hand-in-hand with environmental protection.

Environmental planning begins with the production of an environmental impact assessment (EIA). An environmental impact assessment is a formal approach to evaluating the environmental effects of a project and to minimising environmental degradation in the most cost-effective manner. As part of the feasibility study of a project, it can detect problems at an early stage or minimise expenditure on mitigatory measures.

Procedures adopted involve:

- an assessment of existing environmental conditions;
- a review of the impact on the environment of proposed actions;
- an evaluation of the quality of this impact;
- a definition of appropriate mitigatory and remedial measures;
- monitoring to ensure the effectiveness of control measures.

11.3.3.1 Methods of assessment
An environmental impact assessment is approached in the following way:

- existing environmental conditions (locations, topography, climate, hydrology, flora) are defined;
- those aspects of the proposed project which may have an impact on the environment are defined, e.g. movement of men and machines, structures, waste disposal, aesthetics, changes to storm runoff, changes to the groundwater regime;
- the significance of the impact of each aspect is evaluated.

Good judgement is required to quantify the key environmental parameters. In this regard a multidisciplinary and broad-minded approach is required to define the scope of environment impacts for decision-makers.

11.3.3.2 Remedial measures
Once the aspects most likely to have a significant impact on the environment have been identified, the appropriate remedial or mitigatory measures can be designed. This will normally involve controls built into the design of the project to counter negative effects.

11.3.3.3 Monitoring
Finally, a monitoring system is incorporated. Baseline data on the site and its environs are established before the project starts. Monitoring during the operational phase ensures that the effectiveness of the control measures can be evaluated and, if necessary, improved.

A thorough environmental impact assessment, followed by an on-going monitoring programme, helps to ensure

- that the prevailing legislative requirements regarding environmental pro-
Typical grading curves for various tailings materials.

Figure 11.4. Typical grading curves for various tailings materials.

11.4 Design, Specification and Construction
11.4.1 Operation
11.4.1.1 General
The method of disposal of hydraulically placed tailings to ensure optimum distribution of the particle size fractions varies considerably from one tailings product to the next, principally as a result of the following factors: gradings (particle size distributions), solids content, and solids density.

All these will, to varying degrees, affect the tendency of the material
to segregate, but the most important factor is the grading of the product. A well-graded product with a particle size range from 2 mm to clay fraction, such as is common in copper or platinum operations, will segregate rapidly so that within 30 to 50 m after discharge, the solids remaining in suspension are predominantly fine silt particles. On the other hand gold tailings, which comprise predominantly silt particles and have a reasonably uniform particle distribution, have a much reduced tendency to segregation. Typical grading curves are given in Figure 11.4.

The nett result of segregation differences is that certain methods of disposal which rely on there being minimal gravitational segregation can be used only for tailings similar in grading uniformity to gold tailings. On the other hand methods commonly used in the disposal of copper and platinum tailings, which are designed to optimise the effects of gravitational segregation, are less effective on gold tailings. Gravitational segregation significantly affects the ‘beaching’ profile attained by the tailings. This can, in the case of gold tailings, have significant freeboard implications.

The single most important determinant of beaching slopes for gold tailings is the density of the pulp discharged on to the dam. In this regard typical variations in grading result in much smaller variations in beach slope than those due to changes in pulp density:

<table>
<thead>
<tr>
<th>Pulp water:solids, by mass</th>
<th>Slope</th>
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<tbody>
<tr>
<td>2,15</td>
<td>1:400</td>
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<tr>
<td>1,03</td>
<td>1:200</td>
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It therefore follows that the first aspect to be considered when embarking on a design for a site is the method of development and operation of the proposed tailings dam. The method of operation will dictate: toewall requirements, drainage requirements, penstock locations, and tailings delivery details.

Factors influencing the selection of a particular method of operation and brief descriptions of these methods are set out below.

11.4.1.2 Method of formation of tailings dam
A number of possible methods for hydraulically placing gold tailings exist, namely, the paddock system, the cyclone system, the spigot system, and open-end discharge behind a mechanically formed containment wall.

The choice of disposal methods for a particular project will be determined by a number of factors:

- cost, both capital and operating;
- previous mine experience with one or more of the methods and hence mine preferences;
- site topography – a valley site favours cyclone deposition due to the higher rates of rise while a flat or hillside site favours the paddock system;
- climatic conditions as these affect drying characteristics and freeboard requirements;
- pulp density.
Figure 11.5. Paddock system of tailings dam construction.
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The systems for placing the tailings are described briefly below:

**Paddock system**

The paddock system for dam operation has been developed empirically over the past 100 years and seems particularly suited to the semi-arid and temperate climatic conditions in which most of the gold mines in South Africa are located. The method is illustrated in Figures 11.5a to 11.5c.

Initial construction is carried out to form earth starter walls and under-drainage. The starter walls are sized such that when the tailings reach their maximum height the rate of rise is not greater than 2.5 m/yr. At that stage the tailings themselves are used for wall building. An outer wall is raised by ploughing up a dyke on either side of the wall areas as shown in Figure 11.5c. The wall area is further subdivided into paddocks by cross dykes.

During the day shift, pulp is led from the delivery points along furrows into each of the paddocks and deposited to a depth of about 150 mm. Excess or supernatant water from pulp is decanted into the inner part of the dam. The slurry is left to dry and crack for up to 3 weeks before the next deposition. Deposition in this wall area is carried out only during daylight owing to the high degree of control required on pulp depths. Uncontrolled deposition could easily result in over-topping.

During the night, the tailings are discharged directly into the interior of the dam behind the walls formed during the day.

In view of the emphasis on the two shifts, the outer wall area is referred to as the ‘day wall’, while the inner area is referred to as the ‘night area’, ‘night pan’ or ‘floor’. Supernatant water is drawn off the dam by means of penstock decants or by barge and pump.

On the gold fields of South Africa evaporation generally exceeds rainfall. Provided that rates of rise are low enough, therefore (see Figure 11.2), the surface, with the exception of the pool area, becomes desiccated and large shrinkage cracks develop. These cracks are filled and re-filled by successive lifts of tailings. This desiccation is a fundamental requirement of paddocked dam construction. Drying results in densification, which gives the gold tailings the required strength. In addition the cracks tend to become filled with coarser material, which improves vertical drainage. Rate of rise must be controlled in order to ensure that desiccation does occur. The allowable maximum rate of rise is dependent on tailing moisture content. Figure 11.2 provides a guideline for the maximum rate of rise which can be imposed on the dam.

**Cyclone system**

Increased rates of rise can be tolerated by the gold tailings (up to 7 m/yr and more) by making using of a hydrocyclone to split the incoming pulp into two components:

- cyclone underflow which contains the coarser particles and significantly reduced water content;
- the cyclone overflow which contains the finer particles and most of the water.

Figure 11.6a to 11.6e illustrate the principle of distribution of materials using...
Figure 11.6. Hydrocyclone system of tailings dam construction.
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a hydrocyclone.

The cyclone underflow generally has improved shear strength properties due to the lower water content, is relatively more free-draining than pad-docked tailings, and will form a cone on discharge. The cyclone overflow material, on the other hand, is wet and of lower permeability due to the increased proportion of fines (International Commission on Large Dams, 1980).

The objective in using the hydrocyclone is to place the underflow product in such a way as to create an impoundment for the containment of the overflow. Owing to the lower moisture content and improved drainage characteristics, this material tends to perform better under seismic loading conditions, although in the case of gold tailings where the largely uniform grading of the material results in only a slight difference in coarseness between underflow and overflow, seismic performance is not improved unless the underflow material is well drained and of low moisture content. The most important factor in a hydrocyclone operation is to ensure that the growth of the underflow embankment is at all times significantly ahead of the growth of the fines beach infill behind the embankment. Sufficient underflow material must therefore be available to build the embankment.

The tailings are deposited in a certain sequence using one or other of the downstream, centrel ine, upstream or upstream/downstream placement techniques. These are illustrated in Figures 11.6b to 11.6e. The choice of separation technique depends on topography. The shape of the site defines the required volume of the underflow embankment to contain the overflow product. Geotechnical considerations or drainage constraints may also influence the width of the underflow embankment.

The number and size of the cyclones will also be determined by operator preferences and ease of moving and handling the cyclones, the quantity of tailings, and the need to distribute overflow around the dam perimeter for pool control. Systems in which multiple cyclones are required generally involve more pipework and valves than the paddock system, and depending on the need for cycloning 24 hours per day, can result in increased labour to control operations, particularly during the early development stages of the tailings dam.

These systems tend, therefore, to be used in special cases where:

- high rates of rise of the dam can occur due to the tonnage and topography;
- topography is steep and favours a valley fill tailings dam;
- large freeboard is required for stormwater control purposes in the early stages of formation of the dam;
- high rainfall and low evaporation will reduce natural drying of the tailings and preclude the adoption of a paddock system.

Cyclone systems become less attractive as the perimeter increases. Cycloning is therefore most attractive for valley or hill side dams. The relatively poor split for gold tailings also makes cyclone wall construction difficult.

**Spigot system**
The spigot deposition system is based on the need to ensure adequate drying
Figure 11.7. Spigot system of tailings dam construction.
and drainage of the tailings in the outer wall area by maximising the effects of natural evaporation and drainage. The system involves the use of a pipeline with multiple outlets referred to as a spigoted pipe. Regulated delivery in limited (200 mm maximum) layer thicknesses using a spigoted pipe is carried out. The spigoting encourages runoff of supernatant water directly to the pool concurrent with deposition.

By depositing in thin layers, with a drying period between successive layers, the drainage of each newly deposited layer and evaporation effects are enhanced. The spigot arrangement is illustrated in Figure 11.7a to 11.7c. The tailings deposition front is spread over a length of the ring main, the actual length being a function of the number and size of spigots in relation to the tonnage.

Operations involved in sustaining this system are:

- the construction by hand or machine packing of an outer crest wall for containment of the newly placed material;
- periodic raising of the pipe and extension of the feeds from a ring main.

This usually requires dismantling of the pipe, raising of the supports and re-assembling.

**Mechanically formed containment systems**

The three systems described above have one major common feature — they all facilitate containment dyke construction using hydraulically placed tailings. On large impoundments with long perimeters this feature results in a very considerable cost saving over a system which would involve mechanical formation of the containment dykes using imported materials.

Generally, the South African gold fields are characterised by gently rolling slopes, the exception being the Barberton gold fields. Most tailings dam sites therefore necessitate containment wall construction around the entire perimeter of the impoundment, making long-term operation using mechanically formed (as opposed to hydraulically formed) systems prohibitively expensive. However, mechanical systems do find particular application in the following cases:

- short valley impoundments with a favourable storage to height ratio;
- sites in which seismic activity is of particular concern since earthfill dykes, when correctly designed and constructed, perform better under seismic conditions;
- small operations of limited life.

In view of these factors there are relatively few examples of this method of gold residue disposal in South Africa.

**11.4.2 Tailings delivery**

**11.4.2.1 Pulp concentration**

Within limits it is usually preferred to pump solids at as high a concentration as possible, since in many cases this reduces the size of pumps, pipelines, motors, and power costs. Means for increasing the concentration of solids in the pulp include one or more of the following: spiral classifiers, cyclones,
screens and pressure filters, and thickeners.

All of these have significant capital and operating cost implications which should be offset against: the value and re-use potential of the water recovered, i.e. reduced loss of fluid by avoiding delivering it to the tailings dam; reduced costs of return water recovery; and higher allowable rates of rise.

Maximum concentration may be limited by the thickeners or the metallurgical plant process. In other instances, the maximum concentration may be limited by the adverse effects of high viscosity on pump performance and pipeline losses. Typically, the tailings water: solids ratio varies between 2.8 and 1.0 for uranium and gold and gold-only extraction, respectively. Tailings density is set essentially by process requirements, and modification is not generally economically feasible.

11.4.2.2 Pumping and piping systems

A tailings delivery system comprises pumps, pipelines and valves.

On the vast majority of mines in South Africa, these components are made up as follows:

**Pumps** — usually centrifugal in series, with one variable speed pump to cater for surges. Pumps are usually rubber-lined to reduce impeller wear, and are made of cast iron.

**Pipelines** — in certain cases rubber-lining of the pipe is used to reduce corrosion under acid conditions and infrequently to reduce wear. Delivery columns to the dams are supported on concrete plinths with vertical guide rods to control expansion and contraction. HDPE (high density polyethylene) and asbestos cement pipelines with lower friction and better wear characteristics are finding application on more and more mines. The cost of HDPE pipes is high and problems of fire damage and expansion often necessitate burying the pipe.

**Valves** — types depend on pressure head and the capital cost/operating cost ratio. Certain makes of diaphragm valves which operate at low pressures can be adequate, provided a stock of repaired valves is maintained to facilitate rapid replacement and a routine valve repair programme is maintained. For higher pressures, pinch valves are likely to be the most reliable.

The following guidelines are recommended for the design and operation of tailings pumping and piping systems:

- Avoid sharp bends and steep troughs in the pipeline route. Support the pipe on plinths to regulate vertical alignment. Avoid fixing the pipes to the plinths; opt rather for guides.
- Provide measures to counter expansion and contraction of the pipelines. Position these as close to valves and tees as possible to minimise flange stressing. Expansion control measures can take the form of loops, sections of corrugated armoured rubber piping, free corners or specially manufactured expansion pieces.
- Provide spigots along the delivery line to facilitate flushing in the event of a blockage. Drainage points may be provided at convenient points to
facilitate emptying the pipe for maintenance purposes.

- Implement pipe rotation programmes in areas of anticipated high wear.
- Ensure that valves are placed directly adjacent to tees to avoid blockages between the tee and the valve.
- Allow for surging when deciding on the ratings of valves and flanges. Surge pressures are commonly double design pressures.
- Although external coatings are only required where the pipes may come into contact with the tailings, steel pipes may be coated with a reflecting paint such as high metal content aluminium to minimise temperature differentials. Pipe supports should be high enough to prevent contact of the pipe with the ground or deposited tailings.

11.4.2.3 Pump and pipeline design
Pipeline design and pump selection are dealt with in an Appendix to Chapter 16. Detailed design of the pump and pipeline systems should be carried out by people experienced in the field of pulp transportation.

11.4.2.4 Tailings distribution
In general, the more delivery points there are, the better for operation of the dam. In paddocked dams the spacing of delivery stations should preferably be less than 400 metres. As the relative density of the tailings decreases, control becomes more difficult and it may be necessary to reduce the spacing. For low relative densities particular attention must be paid to locating the delivery stations at corners to prevent the formation of low points. A ringfeed serves the delivery stations which commonly take the in-wall configuration shown in Figure 11.8a. In paddock dams it is becoming more common today to opt for this type of delivery.

In the case of a spigoted delivery, delivery points in the form of spigots are spaced at intervals of between 1 m and 5 m, and are operated in groups of 20 to 40 spigots. The spigots are sequentially opened and closed so that a delivery front progresses around the perimeter of the dam. A ring main around the toe of the dam is provided to feed into the spigot pipe (Figure 11.8b). The number and positions of deliveries into the spigot line depend on the pipe-lifting cycle.

Cyclone systems usually involve connection of the cyclone units into a 'manifold' pipe which is maintained along the crest of the dam. One or more cyclones tee off the manifold pipe at, commonly, 30 m centres. The length of the manifold pipe is a function of operating cycles and sequences, and can be 100 to 400 m. The positions at which the main delivery column connect into the manifold depend on the length of the manifold. An example is illustrated in Figure 11.8b.

11.4.3 Return water management
Storage policies
The Bafokeng disaster of 1974 (Jennings, 1979) demonstrated the importance of sound return water management policies whose cornerstone should be the stipulation that water should not be stored on the top surface of the tailings.
Figure 11.8. Pulp delivery systems for the various types of dam construction.

dam. Ideally water should be decanted off the dam concurrently with deposition so as to maintain a minimum pool area and a depth just sufficient to ensure adequate water clarity. Inherent in this operating philosophy is the need for a return water system which either re-uses or treats the water at a rate at or above the rate at which the water can be decanted, or provides adequate storage in a return water storage dam.

In the first case it may be adequate to decant into a stilling/settling pond whose capacity is limited to that required to ensure adequate water clarity. In the second, the storage facility may act as an evaporation system to pre-
vent discharge of the return water into public streams. In this case the facility may assist in overcoming plant make-up problems during the dry season, and the required storage capacity may be between 30,000 m$^3$ and 1,000,000 m$^3$ depending on circumstances.

Two separate objectives must be recognised in the design and operation of an effective water management programme. These are: i) Minimisation of water loss and hence the minimisation of the cost of water. ii) Elimination of pollution caused by discharge of effluents which do not comply with statutory requirements.

The two objectives are not always compatible, since the cost of water has not yet reached the level where it is a significant proportion of the cost of gold production. For this reason the second objective above must be accepted as a responsibility which cannot always be justified economically.

In order to implement and maintain an effective water management programme, a clear understanding of the plant and mine reticulation network must be obtained. In this regard networks and balances must be prepared and kept up to date. Thereafter, an understanding of the effluent generation and consumption problems on an hourly, daily, monthly and seasonal basis must be sought. Given this information, the reticulation and storage facilities required to eliminate uncontrolled discharge, except in extreme weather conditions, can be designed. The tailings dams produce the most variable and unpredictable quantity of effluent on the mine. In order to understand the effluent generation problems hydrological models can be used. Elements of such a model are:

Inflows: water with the tailings
precipitation
any extraneous disposals such as sewage or concentrated effluents.

Outflows: return water re-use
evaporation
seepage losses
interstitial water (water retained in the pores of the tailings).

Figure 11.9 illustrates typical components of a tailings dam water balance. The difference between inflows and outflows gives the change in storage for the period in question and, in the case of water excess, would be storage capacity required to prevent spillage. In the case of water shortages the change in storage would be the water shortfall for the period. Government regulations (R287) stipulate water storage capacity requirements on the basis of a balance which incorporates average monthly rainfall, and rainfall of recurrence interval 1:100 years of 24 hours duration. Above the storage level obtained from the calculation a freeboard of 0.5 m has been stipulated. This stipulation seems severe but is actually quite realistic. Water balance simulations calculated using actual monthly rainfalls over an extended record period of 50 to 70 years, and using actual area-storage characteristics for the various structures to calculate evaporative losses and rainfall, show that often the maximum volume to be stored calculated over the record is slightly larger than the volume calculated in accordance with the regulation.
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Key:
Tw - Tailings water
I - Interstitial moisture
Swb - Seepage from wet beach
Sp - Seepage from pool
Ewb - Evaporation from wet beach
Ep - Evaporation from pool
P - Precipitation
Rb - Runoff from beach
Rp - Rainfall input to pool
Rxt - Runoff from external pool
D - Decant water from slimes dam
V = Volume stored in Rwd
Dr - Return draft
Rwd - Return water dam

Figure 11.9. Tailings system water network.

Decant systems
Systems for decanting and removing supernatant water from the dam commonly comprise one of the following:

- A penstock decant comprising a pipe outlet of steel or concrete, and a series of inlet boxes with vertical risers.
- Floating barge systems. These systems comprise a primed pump mounted on a raft and located centrally within the pool area. A decant pipe is
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‘floated’ across the pool to the barge and supported above the tailings surface. The pipe is laid over the wall crest.

Commonly, precast concrete penstock rings with effective height of 0.1 m and internal diameter of 0.51 m are used. Alternative materials such as steel and HDPE can also be used. After storms, rings may be temporarily removed to accelerate decanting and then, once stormwater has been removed, the rings may be replaced as appropriate. A decant system which was commonly used until 10 years ago comprised a vertical steel or concrete box with one side open to receive wood stoplogs or weir planks. Some of these systems are still in use today but owing to their poor long-term reliability have been largely superseded by the concrete ring system. The steel boxes and the wood stoplogs degrade, becoming structurally hazardous, and have resulted in many decant failures over the past 30 years.

Steel columns are also used on a number of tailings dams. The columns are extended in sections as the dam rises and are joined by bolts. The column diameter and width of the inlet weir depend on the size of the dam and the rate at which water must be decanted. The weir level is regulated with steel slats which are added or removed to control water level.

Guidelines and cautions on the operation of the concrete ring decant systems based on past experience are given below.

Penstocks
This system is most commonly used on South African gold mines. Despite this fact, a simple, reliable system for locking adjacent concrete rings to yield a riser capable of withstanding tension, such as could be required in seismic events, has yet to be developed. The end faces of the rings are profiled to provide interlocking between adjacent rings against transverse forces.

Dimensional control on the rings has been criticised since out-of-true rings have been found to be responsible for considerable deviation from the vertical (lateral deflections of 700 mm have been measured). A draft specification which will form an appendix to the South African Bureau of Standards Specification 677 for spun reinforced concrete pipes has been prepared (1986) and is currently under review. This draft specification provides for considerable tightening of dimensional control during manufacture.

Penstock risers which have gone off vertical should be brought back into plumb by using a mastic filler between rings.

A number of fatalities have occurred during the addition and removal of rings. Causes have been mainly associated with under-estimation of the force of the water flowing into the penstock. In one case the operator was drawn far enough into the penstock to drown, despite being attached to the platform via a safety harness. Under storm conditions, therefore, management of the rings can prove dangerous and it is advisable to provide suitable platforms and equipment around the inlets to reduce lifting and replacement difficulties with the rings.

Penstock decant structures buried within the tailings dam require structural design where the depth of tailings above or surrounding the structure exceeds 10 m. Elements requiring detailed design are:
The decant pipeline outfall, which should be able to withstand at least the full total overburden stress resulting from the tailings and differential settlements. The bedding and jointing system should allow for movements between pipe sections. The outfall usually comprises a pipe on a bedding. In these cases it is preferable to lay the pipe in a trench to reduce load effects. Both steel and concrete pipes are often used.

The riser or decant, which, as noted above, usually comprises a stack of spun reinforced concrete rings. This riser will have to withstand the lateral pressure of the tailings and frictional down-drag caused by consolidation and settlement of the tailings.

The penstock decant base: this forms the junction between riser and outfall and should be able to support the riser without transferring excess load to the outfall pipe.

Guidelines on the design of the riser and the outfall are given in the Chamber of Mines Handbook of Guidelines (1983). It is, however, advisable to seek professional assistance on decant structures in tailings dams of heights greater than 10 m. By far the majority of failures within tailings dams over the past 10 years have involved penstock structures. None of the failures has been singly responsible for abandonment of the tailings dams and, in most cases, a replacement ‘floating’ penstock has been installed.

Loss of a penstock decant usually necessitates temporary decommissioning of the tailings dam to allow drying for access. The drying and construction period may take 3 to 4 months. Owing to susceptibility to penstock malfunction or failure it is advisable to divide the tailings dam into two compartments with separate penstocks to provide sliming area in the event of failure of one penstock.

Barge systems

Barge systems are seen as being structurally more reliable than the penstock ring system above; however, they do require considerably more maintenance to ensure dependable operation of the pump and to maintain the pipeline above the tailings. In most cases, a barge system is only practical where a large year-round pool is likely to persist. On dams on which the pools are allowed to dry up completely between deposition cycles, the barge tends to ‘bog down’ and is difficult to re-float. To overcome this, some large valley dams have made use of barges on a rail track to raise and lower the barge.

Access to penstock inlets and barges commonly involves one of two alternatives described below:

• A catwalk which usually comprises gum poles (i.e. eucalyptus poles) for uprights between which pine planks are spanned as a walkway. Uprights are periodically extended and a new walkway formed as the tailings level rise. After a number of extensions and a period of exposure most of these catwalks become rickety and dangerous. In addition, over the total period of operation of the dam, catwalk costs mount up and can become excessive.

• A pool wall and limited length of catwalk. This involves the formation
11.4.4 Stormwater management

11.4.4.1 General

A general rule for stormwater management is that all stormwater should be removed from the top of the tailings dam and berms (i.e. paddocks) within one to three days of falling. Penstock inlet or barge pump capacity and any berm decants should be sized on the basis of these average flow rates. As far as is practical, all water accumulating from catchments up-contour of the dam should be routed around the complex and should remain uncontaminated. The regulations stipulate that stormwater which falls within the confines of the tailings dams has to be retained on that dam. This is usually interpreted as meaning that all water which has come into contact with the tailings or blended with any tailings liquor should be regarded as contaminated and cannot be discharged from the complex without a permit from the Department of Water Affairs.

In addition, in view of the need to ensure that water is not stored on top of the tailings dam for any protracted period, the regulations are usually interpreted to mean that the water should be stored for re-use, evaporation or treatment in a separate, specifically designed water-retaining structure, which will constitute part of the tailings dam complex.
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For the top surface of the dam where adequate surge capacity should exist, the intensity of the 1 in 100 year storm of 24 hours' duration may be taken as the total depth of rain divided by 24 hours to give an average intensity. For certain regions of the dam such as the berms or toe catchment paddyards, unlike the top surface, surge capacity is limited and variation in intensity of rainfall within the 24-hour period can prove important. Specific methods to calculate design inflows and outflows have been developed by, among others, the U.S. Soil Conservation Service. These involve the derivation of a simulated rainfall hydrograph with intensities equivalent to 10-minute, 2-hour, 6-hour, etc. storms built into the 24-hour storm. These methods have been computerised and form the basis for most urban and agricultural drainage design.

11.4.4.2 Top surface of dam
The decant system for return water control is usually sized to serve stormwater control requirements as well. The number and sizes of inlets to penstocks and barge pumps are based on an outflow hydrograph over one to three days. Over this period some surge capacity must be provided, and this is usually taken up on the beach slope of the dam. It is considered good practice to ensure that the edge of the pool remains more than 50 m from the edge of the dam at all times. Freeboard of 0.5 m must be maintained over and above the maximum pool level at which this minimum distance is retained.

11.4.4.3 Side slopes
The present approach to stormwater and erosion control of the side slopes of the dam is to maintain a stepped profile of the dimensions shown in Figure 11.11. The rationale for adopting this profile is as follows:

- Limiting the length of the slope face reduces erosion at the toe of the slope. Further reduction in slope lengths would continue to reduce erosion but would prove unwieldy operationally, as each step-back requires the establishment of a new starter wall,
- The berm widths are based on the minimum width to accommodate a crest wall and facilitate machine access for the dressing and maintenance of berms.

It is not recommended that stormwater be retained on the berms and allowed to evaporate as this requires diligent maintenance of the crest and cross walls to ensure that freeboard remains adequate at all times. Uncontrolled spillage over the crest walls can result in severe erosion damage on the side slopes particularly if a cascade develops. In certain cases retention of the water on berms for a protracted period can induce localised stability problems.

It is therefore recommended that berm penstocks be provided as shown in Figure 11.11 at the low points between deliveries (in the case of a paddock dam) or at mechanically formed low points. More details on berm penstocks are given in Section 11.6. Ring inlets will facilitate raising of the inlet invert...
as eroded tailings accumulate from the side slopes on the berms. It is advisable to provide flexible pipes to service the berm penstocks to accommodate anticipated settlements. Further it is recommended that coated pipes or preferably plastic (HDPE) pipes be used to provide long-term corrosion resistance. When constructing the pipe outlets, it is advisable to puddle the trench backfill into place using fresh slurry in order to minimise erosion problems around the pipe at a later stage.

11.4.5 Slope stability
11.4.5.1 Influence of foundation soils
In the design of a tailings dam, and in particular the evaluation of slope stability, considerable emphasis should be placed on obtaining an understanding of the following aspects of the foundation soils:

- grading, and Atterberg limits for correlation of soil types;
- permeability at varying stress levels;
- consolidation characteristics in cases where rates of rise are to be particularly high or where soils of low permeability occur;
- shear strength.

Where feasible the above parameters should be obtained from tests in which actual tailings liquor is used in order to verify that no obvious hydrogeochemical effects occur which could change the behaviour of the foundation material. Figure 11.12 illustrates the influence that foundation drainage can have on the position of the water table or, in geotechnical terms, the phreatic surface, for four drainage conditions. Slope stability is particularly sensitive to the position of the phreatic surface, in relation to whether it intersects the slope or passes into the foundation before reaching the slope. Low permeability soils with poor consolidation characteristics will, particularly under high rate of rise conditions, generally have low shear strength and could impose limitations on the height and slope angle of the tailings dam.

11.4.5.2 Influence of tailings product
Geotechnically the gold tailings product may be described as a rock flour comprising 0–15% fine sand and 0–10% clay fraction with some 80% of
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Figure 11.12. Effect of differing foundation \(k_f\) and dam \(k_d\) permeabilities on position of phreatic line (after Blight and Steffen, 1979).

the material falling within the silt classification. The clay fraction arises from the grinding of fresh rock and therefore possesses few of the properties usually associated with clay. All particles tend to have a granular as opposed to plate-like shape as is the case with clay. Gold tailings exhibit no plasticity and no cohesive characteristics. Although in pyrite-rich products some crusting of the dried outer surface may occur, this crusting is purely superficial and is not evidence of cohesion within the body of the dam. The effective angle of friction of fine gold tailings such as would be found around the penstock is the same as for coarse tailings at the delivery on to the dam. The important difference between the coarse and fine products lies in their permeability and consolidation characteristics. The fines will take longer to consolidate and, if loaded too rapidly, the available shear strength can be reduced by excess pore pressures.

Differences in grading, permeability and shear strength between fine and coarse products are, in the case of gold tailings, not as pronounced as with coarser products such as platinum or copper tailings. The maximum difference in permeability can be one order of magnitude (factor of 10) but is usually less. Some layering does occur due to variations in directions of deposition and paddock filling. Variations in the milling consistency, however, may give rise to greater variations than segregation during deposition. However, desiccation cracks and the preferential filling of these cracks with coarser material on the next deposition cycle, tend to reduce the effects of layering so that vertical permeability is only some 1.5 to 3 times lower than horizontal permeability. Distribution of finer and coarser fractions along a beach will be similar for the paddock and the spigot systems, and provided delivery points are positioned in accordance with the recommendation in Section 11.4.2.4, this will be the case along the day/crest wall as well. Finer material will therefore be concentrated towards the pool area with coarser material around the perimeter.
Cyclone deposition is usually specifically designed to give a materials distribution where adequate coarser fraction is placed as a confining embankment to retain the finer overflow product. In this case differentiation of material properties from a slope stability viewpoint may well prove more important particularly as regards permeability and the control of the phreatic surface.

11.4.5.3 Influence of rate of rise
Rate of rise is the term globally applied to describe qualitatively the controlling influence of drainage and consolidation. High rates of rise on poorly draining soils can severely affect
- the position of the phreatic surface — with severe stability implications;
- the degree of consolidation of the foundation soil and hence the shear strength of the tailings;
- operation of the dam in cases where cycle times prove inadequate to facilitate drainage drying and desiccation of the daywall tailings. In the case of paddock dams this could result in piping through the pack-out walls (i.e. the dykes) when new deposition takes place. Inadequate drying will also affect access for packing-out tailings (i.e. dyke building).

The influence of rate of rise on slope stability is illustrated in Figures 11.13a and 11.13b. The figures were derived for a factor of safety = 1.5. These do not necessarily give the controlling condition since operational constraints such as access may be more stringent. Reference in these instances should be made to Figure 11.2.

11.4.5.4 Influence of phreatic surface
The position of the phreatic surface is the parameter to which slope stability is the most sensitive (where stability of the tailings rather than the foundation soil is critical). This has been demonstrated both in the theoretical analysis and in field observations of failures. It therefore follows that in cases where slope stability has to be improved, any measures which beneficially influence the phreatic surface will prove the most effective. Up to the 1960’s it was common practice to initiate and operate a gold tailings dam by dozing up a toe starter wall and commencing deposition. Fortunately in most cases the rates of rise and foundation drainage conditions were such that no severe stability problems were experienced, at least not usually until a dam height of 15 to 20 m was reached. Seepage erosion at the toe of the dam has in the past often been remedied with expensive rockfill buttressing. The efficiency of these buttresses was, however, reduced as the interstices of the rock became clogged with slime. This clogging causes the phreatic surface to rise further; eventually large scale instability can occur. Correct design of buttresses is therefore a prerequisite for long term performance.

In 1959 the first under drain was placed at the toe of a new section of a gold tailings dam in the Orange Free State (National Building Research Institute, 1959). This drain was constructed of specially selected materials to ensure a gradation from fine tailings to coarse rock so that only water
and no tailings would enter the drain. The drain still operates to this day. The objective in deciding on placement of drains is to provide a control point well inside the toe of the dam to which the phreatic surface can be drawn, thus maintaining a dry slope face. Today drains in slimes dams are the norm and this coupled with other modern design concepts has increased feasible dam heights from a maximum of 30 m to 60 m and more. Figure 11.14 illustrates the effect of an underdrain.

Even with the inclusion of an underdrain, poor deposition practice, high rates of rise, variable material distribution, and poor pool control can negate many of the positive influences of the underdrainage. It therefore follows
that the provision of underdrainage goes hand in hand with good operation in improving slope stability and increasing maximum final height.

11.4.5.5 Influence of slope geometry
Figures 11.13a and b above illustrate the influence of slope angle on slope stability. It is of interest to note from the graphs that a relatively small reduction (2 to 6 degrees) in slope angle can result in a very large increase in height of dams and a proportionally large increase in dam capacity. Present practice is to adopt even flatter effective slope angles than those considered in drawing up the graphs in Figures 11.13a and b. The reason lies in erosion
and stormwater control requirements. In Section 11.4.4 a recommended slope profile was described which involved the creation of stepbacks and the provision of berm penstocks. This profile results in an effective slope angle of 25 degrees. It is the authors' opinion that the slope volume sacrificed by adopting a flatter angle is offset by the benefits of improved slope erosion control and the potential for even greater allowable height.

11.4.5.6 Stability analysis
Several methods for analysing slope stability exist, ranging from those involving charts developed from specific geometric conditions to sophisticated computerised calculations able to cater for almost any slope geometry. By far the majority result in the calculation of a factor of safety which would represent a ratio of resistance to disturbance as a quotient of forces, moments or shearing stress. Other analytical approaches exist, the most important of which is probably that of finite elements. In this analysis the slope is divided into a mesh of elements with connecting nodes.

There is a trend in slope stability analysis at present to opt for probabilistic type analyses; most of these involve the calculation of a distribution of factors of safety and from them in turn a deduction of the probability that the factor of safety is less than a given amount. The principal rationale behind probabilistic analysis is that unlike pure factor of safety evaluations, probabilistic analyses are linear. By this is meant that halving the probability of failure makes a slope twice as safe, whereas doubling the factor of safety makes the slope safer by an unquantifiable amount. Factor of safety is therefore really a qualitative measure of safety, while probability of failure is a quantitative measure. Probabilistic methods are still very much in the early stages of development and have a short track record compared with tried and proven factor of safety methods.
11.4.6 Repair and reinstatement of operational and abandoned impoundments

11.4.6.1 Common problems with old and abandoned dams

It has only been over the past 10 to 15 years that a trend towards systematic design coupled with detailed geotechnical evaluations of new tailings sites has developed. Consequently there is a large number of tailings dams which are still operational but are exhibiting problems. In addition, as a result of increased land prices and environmental issues, there is an increasing tendency for mines to look to re-commissioning old, previously abandoned, impoundments. Repairing existing troublesome impoundments for which infrastructure such as pipe networks and access are in good working order usually involves expenditure on civil works similar to that for a new dam. However, cost savings considerably larger than these expenditures result from eliminating the need to provide new pumping and piping systems and the avoidance of land purchase costs. In the case of re-commissioned dams, land purchase costs are avoided and, since these dams are usually located closer to the plant than the newer sites, the pump and pipework costs are usually lower.

The commonest problems exhibited by troublesome dams are: seepage erosion at the toe resulting in slope instability; a high phreatic surface resulting in general slope instability; inadequate deposition area resulting in excessive rates of rise, poor consolidation and drainage, in turn inducing the previous two problems. Inadequate area more often than not results in a commitment to obtaining additional area for a supplementary new development or a dam extension. Even in this instance savings can be effected by purchasing only sufficient land to supplement the repaired existing dam as opposed to completely replacing the dam.

Almost invariably the source of these problems can be traced back to phreatic surface control. Even in cases where the dam is on weak foundations, significant lowering of the phreatic surface can improve stability drastically. Often the old dams suffer from the following geometric problems:

- The penstock is located close to the edge of the dam, causing the pool to be off centre. Usually, owing to the original ground topography, the penstock is established in the topographically low regions which correspond with the tallest side of the dam. Close proximity of the pool at the edge serves to accentuate seepage erosion and phreatic surface problems identified above.

- Too few deliveries are provided, resulting in long runs along the daywalls, poor pool control and low freeboard furthest from the deliveries.

- Slope faces are maintained too steep with few stepbacks. This has implications concerning both slope stability and stormwater erosion.

- The penstock pipes and inlets are rickety and unsafe through deterioration of pipes and inlet structures. Often these ‘hole through’ and draw tailings into the penstock with the resultant formation of a sinkhole around the inlet or along the penstock line.
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(a) Mechanically placed buttress

(b) Hydraulically placed buttress

(c) Cut-to-fill buttress

(d) Cycloned buttress

Figure 11.15. Various types of wall buttress.
11.4.6.2 Remedial measures
Remedial measures usually involve one or more of the following:

Adjustment of slope geometry
This may involve:

- Buttressing using mechanically placed materials such as earth and rock or tailings (see Figure 11.15a). Note the placement of a drainage medium between the original tailings and the buttress for phreatic surface control. Mechanical buttressing is usually undertaken where remedial action is urgently required.

- Buttressing using hydraulically placed tailings by forming ‘mini’ dams around the toe. Each dam has its own penstock, and is underdrained (see Figure 11.15b). This buttressing method can be cheaper to form than a mechanically placed buttress, depending on buttress height.

  Since buttresses can normally only be built on the dayshift, freeboard is sometimes lost on the main dam if insufficient slime is available to build daywalls. This becomes a serious limitation where rates of rise are high or where slime density is low. However, formation of hydraulically placed buttresses takes time and needs to be done with care to avoid artificially lifting the phreatic surface in the main dam and inducing slope failure.

- Pushdown operations where the effective slope of the dam wall is reduced (see Figure 11.15c).

- Effective reduction of the slope angle using cyclone underflow (see Figure 11.15d). Disposal of the cyclone overflow can become problematic if the dam already has a stepback. In this case a slurry tank and pump may be required to lift the overflow into the floor area of the dam.

  Generally, hydraulically placed options are low on capital cost but high on operating costs. Mechanical buttressing therefore often proves to be more effective when all costs are considered.

Adjustment of pool location and top surface geometry
Seepage and phreatic conditions within the slope can be considerably improved by relocation of the pool so that the edge of the pool is maintained a distance of 100 to 200 m from the crest of the slope. This usually involves the installation of a ‘floating’ or elevated penstock. A pool wall can assist in reducing penstock pipe lengths and reducing catwalk costs as illustrated in Figure 11.16.

Improved delivery system
The addition of delivery points to meet criteria proposed in Section 11.4.2.4 can increase cycle times and drying characteristics of the dam. Pool control and freeboard can also be improved.

Installation of drainage
A number of methods for installing slope drainage in an existing slope exist, two of which are:

- Elevated drainage – this involves the construction of drainage blankets
Figure 11.16. Pool relocation.
Future phreatic surface – no drain
Future phreatic surface – with drain
Elevated drain
Drain outlet
Phreatic surface at time of installing drain

(a) Elevated drainage

Phreatic surface without drains
Phreatic surface with drains
Push-in drain

(b) Push-in drains

Figure 11.17. Incorporation of drainage into established walls.

on the top surface of the dam with the aim of controlling the phreatic surface during future operations (see Figure 11.17a). Water accumulating in the graded filter blankets is drawn off the dam through flexible outlets.

- ‘Push-in’ drains – these comprise slotted pipes wrapped with geofabric (i.e. synthetic filter membrane) and are drilled or wash bored into the toe of the dam as shown in Figure 11.17b. The pipes form wick drains and, if placed closely enough, can be effective in controlling seepage at the toe. Access problems and wet and often dangerous working conditions at the toe often preclude this method as a viable option.

Construction difficulties and sensitivity to design assumptions make these methods difficult to implement correctly.

11.5 Observation and Control

The adage, a stitch in time saves nine, is nowhere more appropriate than when used in reference to tailings dams. It is the authors’ experience that
the introduction by mine management of formal observation and control procedures has, almost without exception, led to an improvement in mine and operator personnel awareness. On the majority of mines, however, slimes dam observation and control are still usually related only to pumping problems and problems associated with plant downtime. Routine aspects of matters such as the following are either ignored or glossed over: pool control, rate of rise, slope geometry, physical condition of key structures such as penstocks and access ways, erosion control on side slopes and along stepbacks, catchment paddock and solution trench maintenance, deposition sequencing, phreatic surface control, and drainage operation. In many cases one or more of these aspects is responsible for serious problems with the tailings dams. Problems could either have been avoided or remedied while access was easier and costs lower had monitoring been effective. It is recommended that formal procedures for reviewing and discussing these features be entrenched in all tailings disposal operating procedures on a quarterly or a six-monthly basis. What is most important is that the review be done at senior management level to ensure that the consequences of developments on the tailings dam are appreciated at first hand by those legally responsible for the safety of the dam, and that discussions on remedial action and approval of monies to pay for this action are taken with minimum lead time.

Depending on the specific state of the dam and the consequences of a failure, it may be prudent to retain the services of a professional engineer specialised in the fields of geotechnical and tailings dam engineering to review the dam operation.

A good observation and control system will necessitate the services of a surface surveyor to:

- survey cross sections regularly and establish the heights and positions of instrumentation, calculate rates of rise, and check on slope geometry;
- monitor instrumentation such as piezometers which are installed to locate the phreatic surface;
- make observational notes on the location of the pool, the status of the penstock inlets and access ways, erosion problems, maintenance aspects and drainage operation.

Instrumentation which is commonly installed on tailings dams includes:

- Piezometers, which are used to measure pore water pressure in the tailings or foundation soils, and provide an indication of the position of the phreatic surface. Types of piezometers are:
  - i) Standpipe piezometers which comprise a vertical length of pipe positioned in the side slope or on the top surface of the dam with a porous tip inserted below the phreatic surface. Water enters the tip and rises in the tube to a level indicative of the piezometric head or pore pressure at the tip. The water level is then measured by using a remote sensor lowered down the tube to the water surface. The depth of water is usually plotted on a cross section for interpretation purposes.
  - ii) Pneumatic piezometers which are installed at specific points in the
tailings and foundation soils. These units comprise a porous tip and a diaphragm. Tubes filled with nitrogen are led from the unit to a point outside the dam where they are connected to an instrumentation board. A remote read-out unit which pressurises the nitrogen until the external water pressure on the diaphragm is balanced is used to measure the pore pressures.

iii) Vibrating wire piezometers which rely on water entering a porous tip as with pneumatic piezometers, and causing a diaphragm to distort. The diaphragm is connected to a thin length of specially designed wire surrounded by a coil. Contact leads are led to a terminal board outside the dam from which a current is passed through the coil. The current induces vibration of the wire at the diaphragm and, since the frequency of vibration of the wire is a function of the tensile stress in the wire, through a series of conversion and calibration factors, the amount of movement undergone by the diaphragm as a result of the water pressure may be deduced from a remote read-out.

- Inclinometers, which are used to measure progressive slope movement. These instruments comprise specially shaped, vertically grooved tubes which are drilled vertically into the section until the bottom of the tube is in material which is unlikely to move. The tube is then fixed at the base using concrete. A probe is lowered into the tube along the grooves. Within the probe is an inclinometer which, through a read-out, permits measurement of the angle of inclination of the probe. By taking a series of measurements up the tube starting at the bottom it is possible to compare consecutive measurements and plot a profile of the inclinometer readings showing cumulative changes in slope. Trends from one set of measurements to the next can be used to assess the rate of movement and the horizon along which movement is predominantly occurring.

- Other simpler forms of instruments which may comprise survey pegs or extensometers which would be used to detect local movements of the surface.

Figure 11.18 shows a typical section and locations of standpipe piezometers.

The various depths which are measured and recorded are indicated in a cross section on the record sheet. It is worth noting also an estimate of
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the distance from the daywall to the pool. This is useful when interpreting piezometer levels, since a close pool will often explain a sudden rise in phreatic surface.

Concluding this section on observation and control, it is worth stressing the importance of documenting all discussions and review comments in minute form. If an action column is included on the minutes there will be increased urgency for the person responsible to carry out the decisions taken during the review. It should also then be recorded when the action is taken so that a chronological record is developed of all problems and remedies. Attached to the minutes should be the piezometer measurement records, plots of cross sections and any other reports worth putting on record. At regular intervals the measurements, together with the recorded comments, and the present dam status should be reviewed by a professional geotechnical engineer who should then undertake to produce a report documenting all comments and formalise into report format instrumentation readings and notes made during the period of review.

11.6 Closure Considerations

11.6.1 General
Closure procedures for a gold tailings dam must comply with the requirements of the Air Pollution Prevention Act, the Mines and Works Act, the Health Act and the Water Act, in order to prevent pollution of surface and underground water resources and of the atmosphere and to treat the dam so that it and its appurtenant works require as little maintenance as possible.

The closure of a tailings dam involves considerable expenditure by the owner. If the desired result is achieved, this expenditure is justified because an unstable generator of nuisance and a source of pollution is converted into a stable, permanent topographical feature with little adverse environmental impact and a low maintenance cost.

In addition to these basic objectives, attention should also be given, at closure, to the other possible benefits of properly closed dams. For example, whether it will be possible to use the tailings dam as a clear water catchment, transform the tailings dam into a scenic feature, or to use the tailings dam or any of its appurtenances for recreational purposes.

11.6.2 Boundary fence
Uncontrolled access of people, animals or other traffic to a closed tailings dam must be prevented by installing a properly constructed and maintained security fence. Current costs for installing a 2 m security fence are three to four times those for a 1,2 m high fence, as shown in Figure 11.19. As the cost difference between the two systems is substantial, the requirements of the Chamber of Mines Guidelines should be interpreted with particular reference to the cost effectiveness of the chosen system. The location of the tailings dam should dictate the type of fence that is necessary. For example, a security fence should be considered in cases where the dam is adjacent to a built-up or residential area. However, lower cost fencing should be suffi-
Figure 11.19. Typical fencing details (after Smith, 1983).

Figure 11.20. Closure methods for effluent trenches (after Smith, 1983).
cient for dams in sparsely populated rural areas. The effectiveness of the fence system is dependent on the level of maintenance. The only feasible approach appears to be to form a body of rangers whose duties are regularly to inspect and repair all fences in their region.

11.6.3 Access roadways
The access road requires periodic maintenance to ensure continued access to all parts of the tailings dam for inspection. The maintenance envisaged is limited to low-cost operations. Typically, this involves repair of erosion gullies and large potholes and clearing of encroaching vegetation.

11.6.4 The underdrainage system
To ensure continued stability of the slopes the phreatic surface should be kept permanently low. This requires that the existing underdrainage system function continuously after closure. The drainage outfall pipes should be marked clearly or staked and kept free of silt and vegetation to allow unhindered flow at the outfalls.

11.6.5 The solution or effluent trench
Problems associated with effluent trenches, both during operation of the dam and particularly after closure, can be summarised as follows:

- sloughing of the side walls, which leads to siltation of the trench, is a common phenomenon (the extent of sloughing depends on the soil type and the depth of the excavation);
- water velocities which depend on the grade of the trench can result in either scouring or siltation. Uncontrolled vegetation in the trenches can adversely affect the flow characteristics and performance of the trench;
- although the dam may be fenced, open trenches up to 2 m deep in places are a danger to trespassers such as stray livestock, domestic pets and particularly children.

To eliminate or reduce these problems, recommended closure procedures for effluent and solution trenches are:

- where no underdrains discharge into the solution trench and where the benefit of the solution trench acting as a seepage cut-off trench is not evident, the closure procedure as described in Figure 11.20 (Alternative 1) is recommended, e.g. backfill the trench with selected, nominally compacted earth;
- where underdrains discharge into the effluent trench and/or where the trench acts as a seepage cut-off facility, construct a maintenance-free ‘closed’ drain system as described in Figure 11.20 (Alternative 2), i.e. line the sides and bottom of the trench with a geofabric prior to backfilling with a clean, free drainage material (clean dump rock or aggregate).

Complete the ‘drainage sock’ by extending the side wall geofabric over the top of the rock and then backfill the top 300 to 500 mm section of the trench with selected earth backfill as in Alternative 1. The high capital costs
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required to implement these procedures are justified when they are compared with the cost of maintaining open trenches for the continued life of the deposit.

11.6.6 The slimes delivery pipeline
The slimes delivery column from the plant to the dam and around the dam perimeter and all valves and slimes delivery pipes should be dismantled and removed from site. If the slimes delivery pipes are ‘in wall’, the closure procedures illustrated in Figure 11.21 are recommended. The pipe ends should be blanked off after the pipe has been filled with mass concrete. To prevent piping erosion where the pipe enters the toe of the dam, a filter arrangement should be installed. This can be achieved by cutting back into the toe and installing a geofabric and rock or sand and rock filter.

11.6.7 Surface drainage
Drainage of the surface and sides of the tailings dam is influenced by the geometry of the dam. The recommended water control features for each of the tailings impoundment components as illustrated in general in Figure 11.22 are outlined below.

11.6.8 Ground level catchment paddocks
After closure of a dam, a detailed survey of the catchment paddock area is undertaken to optimise the location, number and dimensions of compacted crosswalls. Crosswalls should have interleading, hydrologically sized spillways to ensure an equal distribution of stormwater around the dam perimeter. These measures maximise the evaporation potential of the available paddock area. Interleading spillways and an emergency spillway from the topographically lowest paddock to the evaporation or storage dam area minimise the risk of overtopping or breaching or both of catchment paddock walls during excessive rainfall.

Before the construction of spillways and crosswalls, the catchment paddock wall should be examined and checked for structural competence and size (i.e. available freeboard and capacity). Consideration should be given to covering the outer paddock walls, division walls, and the lower reaches of the impoundment wall with dump rock to protect them against erosion when water is stored against them.

11.6.9 Berms or step-backs
There are principally two ways to control stormwater that falls on berms and the side slopes above the berms. The first involves discharging water from the terraces by means of spillways or penstocks into the ground level catchment paddocks. Spillways and penstocks are located at each of the low level points along the berm about midway between each of the original slimes delivery stations. The spillways are formed by combination of rock mattresses and gabions (i.e. rock-filled wire baskets) over a prepared, compacted geofabric-lined surface. At the base of the spillway, within the catchment paddock, a reinforced concrete apron is provided. To ensure that water flows
Figure 11.21. Closure procedures for 'in wall' delivery pipelines (after Smith, 1983).

Figure 11.22. Plan of typical paddock wall (after Smith, 1983).
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freely along the berm to the spillway or penstock, and to prevent spillage and erosion of the lower side slopes, terrace preparation is important. One method includes shaping of the berm with a 5% fall inwards towards the slope of the tailings dam and provision of stone pitching along the flow path to prevent scouring or erosion. Another alternative consists of a lined or protected trench or bund on the outer extremity of the berm.

The second method of controlling stormwater on berms and side slopes entails the storage of all water on the terraces. Design criteria are the same as those for ground level catchment paddocks. The lowest level berm paddock is provided with an overflow penstock or spillway to route surplus water to ground level paddocks. For both methods, the establishment of vegetation cover of the surface of the terrace is recommended to minimise contamination of rainwater by transportation of solids, and wind erosion during dry windy periods.

Of the two methods, the first is preferred as it ensures that all water and silt, eroded off the slopes above the berm in question, are transferred to the catchment paddocks at ground level. It is easier to deal with water and eroded material at ground level than part way up the dam. The effectiveness of the second method is less assured since the ability of walls formed with tailings to impound water is questionable.

11.6.10 The dam surface
The surface of the tailings dam is subdivided into two areas, the daywall and the basin. The existing surface topography should be used to control rainwater falling on the area. The most economic solution is to provide rock mattress spillways to discharge water from the daywall into the basin area. Spillways should be provided at low level points, midway between each of the original delivery stations. Water discharged into the basin flows to the central penstock or spillway. All surface runoff is directed to and controlled at the central penstock or spillway. From there it is discharged to a storage or evaporation dam. As shown in Figure 11.23, there are two ways to decant water from the surface of the dam.

The first method (Alternative 1) is applicable to dams with adequate penstocks. In this case penstocks may be used as spillways to discharge water to the evaporation or storage dams. Details include no-fines concrete penstock rings above the slimes level, surrounded by a sand filter layer to allow drainage of water. Penstock rings can be added to a level higher than that of the basin in order to ensure that only clear water is discharged, even during heavy precipitation.

The second method is applicable to retired dams not equipped with adequate penstock system or systems of doubtful long term integrity. In this case penstocks should be sealed as shown in Figure 11.24, and a surface spillway or trench arrangement provided as detailed in Figure 11.23. This system consists essentially of a rock mattress-lined trench from the pool and towards and through the daywall. Flow down the sides is controlled by a gabion spillway similar to that described for the berm spillways. A weir at the edge of the pool area should be provided for discharge control. As in
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Typical section of penstock decant arrangement (Alternative 1)

Typical longitudinal section of decant trench

Figure 11.23. Details of water decant arrangements (after Smith, 1983).
Figure 11.24. Penstock closure methods (after Chamber of Mines of South Africa, 1983).

the case of the outer berms, the top surface of the dam perimeter and crosswalls, daywall and basin should be compacted and stabilised using vegetation. This minimises and reduces wind and water erosion from the top of the dam.
11.6.11 Return water dam
Only clear water from the top of the dam should be discharged to the return water dam, so that the return water dam may be used as a clear water reservoir. If necessary, at the time of closure, it must be put in a condition such that it will operate safely and with minimum maintenance for the foreseeable future. The water in the return water dam could be used for irrigation, discharged into the natural drainage system, used to recharge underground water, or used for fish-farming, recreational fishing or water sports. To ensure high quality water, the owner should be prepared to consider stabilisation and hardening of the top surface of the slimes using lime or cement to minimise contamination by silt and dissolved salts.

11.7 References