Chapter 5
Engineering Design

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> *All projects are intended to have an impact on an environment.*
> —Jean Paul Sartre

Mineral extraction and processing operations result in a significant volume of coarse and fine mine waste materials and, though a proportion might be recyclable, the majority require storage in purpose-built mine waste facilities. The coarse waste (labelled as mine waste rock in Fig. 2.2) is generally stored in mine waste dumps on surface or used for backfilling mining voids, though that with suitable characteristics may be used for infrastructure development, including a MWF. The fine waste (labelled as hydraulic fill in Fig. 2.2), the principal subject of these guidelines, derived from the mineral processing is likely to be transported hydraulically and deposited into a purpose-built reservoir, invariably stage-constructed throughout the operating life of the project. Such a facility needs to be designed to accommodate both the fine extractive waste, the process water and, on many sites all local runoff, and to be designed and constructed in accordance with good practice in order to achieve safe storage and to comply with all statutory requirements throughout its operating life and beyond. This Chapter reviews the principle design characteristics of a MWF, with particular emphasis on a risk-based approach.

5.1 Background to Design

MWFs are among the most visible legacies of an extractive operation and, after closure and rehabilitation, are expected to be stable and to have no detrimental effects on the environment, effectively in perpetuity. Poorly designed or badly managed waste facilities lead to higher closure costs, to ongoing impacts to the environment and to an increased risk to public health and safety. Mining companies therefore face the challenge of

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effectively and efficiently managing MWFs throughout their life-cycle, from initial site selection and design through construction and operation to eventual decommissioning and closure. Responsible corporate entities therefore need to prescribe internal health and safety strategies which include a specific policy for the hydraulic transport and storage of extractive wastes against which operational standards can be developed and subsequently managed. This policy will normally contain business, operational and environmental objectives which can be developed within the framework of the prevailing regulatory and legislative environment. The role of the Regulator is to confirm that these objectives are consistent with EU and national waste management and environmental policy, to permit the facility, to set compliance targets and to ensure that the MWF remains fully compliant both with Regulations and permit conditions throughout its life and beyond.

The engineering design of a waste management facility is complex and must be undertaken by competent consulting engineers with relevant experience in order to meet the requirements of cost-efficiency, safety and stability, as well as compliance with planning, environmental regulations and closure strategy. The design of a mine waste facility should therefore include the following provisions:

- safety—design and construction to meet both short- and long-term geotechnical and geochemical stability requirements;
- economy—use of mining waste, where appropriate, for confining embankment construction;
- water management—maximisation of water recycle and re-use whilst managing flood events in safety;
- facility management—operation, inspection and monitoring in accordance with good practice and with statutory requirements;
- environmental management—control and monitoring of all potential emissions against compliance targets;
- closure—design of facility at mine closure to achieve a sustainable landform which minimises long-term liabilities and impacts.

The principles of tailings and waste management best practice should be founded on a risk-based approach to planning, design, construction, operation and closure, as described in these guidelines. Such an approach, predicated on an understanding of all potential failure mechanisms, enables consideration of alternative solutions and the establishment of a design basis which meets internationally recognised good practice. This Chapter provides an overview of the engineering design and risk assessment process (civil, geotechnical and environmental) together with the derivation of the key project parameters enabling the design criteria for all stages of project development to be defined (Table 5.1).

Table 5.1 Waste facility development phases

Regulatory	Project phasing	Investigation and review phases
Pre-development	Project initiation	
	Conceptual design Prefeasibility study	Desk study Regulatory scoping study Environmental scoping study
Permitting	Feasibility study	Phase I site investigation Environmental baseline study Preliminary facility characterisation Preliminary material characterisation
	Design Project approval	Phase II site investigation Environmental impact assessment Facility characterisation Waste characterisation Emergency planning Independent design review
	Pre-deposition construction Operating permit	Construction CQA Preparation of as-built drawings Preparation of operating and maintenance manual Independent inspection and reporting
Compliance	Operation Annual compliance reporting	Inspection and monitoring Waste characterisation Stage construction design/CQA/Approval Preparation of as-built drawings Revision of operating and maintenance manual Update of emergency/closure plans Annual independent inspection and reporting
Closure	Active closure Compliance reporting	Implementation of closure plan Initiation of facility rehabilitation Inspection and monitoring Annual independent inspection and reporting
	Passive closure Final compliance reporting	Completion of closure plan Initiation of long-term rehabilitation and maintenance plan Initiation of long-term inspection and monitoring plan Independent inspection and sign-off

5.2 The Design Process

5.2.1 *Mine Waste Disposal Principles*

The fine residues resulting from the refining of a geological resource in the process plant generally comprise a sandy silty particulate waste which is discharged in slurry form. Such materials, regardless of their consistency, need to be placed in a secure containment facility and, in most cases, would not be stable without being suitably confined. The cost-efficiency of the refining process and the site water balance generally necessitates that the greater part of the water contained within the slurry be recycled and re-used. Thus any containment facility should include capacity for both the hydraulic fill and a process water storage and recycle element. The residue is usually pumped from the plant to the storage facility as a hydraulic fill (slurry), the consistency of which will vary depending on the economic material, the refining process adopted and the configuration of the storage basin. The slurry may take the form of a very thin pulp with low solids concentrations (<5%), as for many silt lagoons, or be thickened to between 70 and 80% solids and be deposited as highly-thickened tailings. The consistency of the hydraulic fill will determine the construction of the confining structure, the sedimentation and return water (decanting) system incorporated into the MWF and the proportion of clarified industrial water to be returned to the plant for re-use. The purpose of a mine waste management facility is therefore twofold, namely:

- to provide a cost-effective and environmentally appropriate means of storing the waste and of recycling the process water;
- to provide safe and stable storage of the waste such that at closure the facility achieves geotechnical and geochemical stability.

The engineering design process for any MWF therefore requires the development of the following:

- a strategy for the placement and storage of the extractive waste materials;
- detailed characterisation of the various extractive waste materials to be stored;
- investigation of potential placement environments, both physical and Regulatory;
- detailed description of the physical, environmental and Regulatory factors associated with each potential storage location;
- development of alternative design elements to meet strategic objectives and to mitigate all potential impacts;
- development of an understanding of all MWF failure mechanisms and of their risk ranking;
- selection of the optimum design configuration for the MWF, fully supported by appropriate qualitative and quantitative risk analyses;
- the establishment of an implementation schedule for the selected MWF;
- the design and implementation of a quality assurance programme to monitor the design, construction, operation and performance, including the ongoing assessment of potential failure mechanisms;
- the development and implementation of inspection routines for the waste facility at all levels of operation and management;
- the initiation of independent expert and Regulatory auditing, together with the ongoing review, analysis and reporting of the data and information gathered in order to:

- confirm ongoing safety, stability and Regulatory compliance;
- apply the lessons learned for future facility design, construction and operating practices;
- improve knowledge of potential failure mechanisms and methods of mitigating downstream impacts.

5.2.2 Basis of Good Design

Engineering design is based not only on technical knowledge but also on an appreciation of the process of developing solutions within a systematic and unified framework. The nature of the design process can therefore be characterised as follows:

- Hierarchical—the development of an understanding of the complexity of each design element and its inter-relationship with the project;
- Functional—the creation of a product which will perform in a satisfactory manner;
- Evaluation—the selection of the most appropriate engineering solution from the options considered;
- Iterative—the ongoing co-ordination, modification and improvement of the design objectives and function;
- Optimisation—the creation of an optimal coherent design system.

Solving practical engineering problems involves more issues than those of simply developing complex technical parameters. The design, operation and closure of a mine waste facility encompasses a broad spectrum of technical skills, from civil and structural engineering to environmental management and impact assessment. The range of expertise required must be recognised from the onset if the facility is to meet its design objectives and achieve successful implementation. In addition, the application of the various technologies to be adopted must be managed to ensure that they are fully integrated and that the necessary assessments have been undertaken at each stage of the process to ensure that all risks are fully mitigated. The key elements in the assessment of risk are defined below, noting that the role of the engineer is to identify the hazard, risk and consequence and minimise any impact throughout the life of the project:

- hazard—a source of danger or risk;
- risk—a chance of danger, injury or other adverse consequence;
- probability (Pr)—the likelihood of death, injury or damage occurring;
- consequence—ranging from none to death, injury or damage;
- risk assessment—the identification of all potential hazards and their risk of occurrence—simplistically, a sophisticated term for a “what if?” analysis;

- risk mitigation; the reduction of probability of occurrence to the highest acceptable rate of death, injury or damage, a value generally determined by societal norms;
- risk management—engineering design, operation and closure to achieve the agreed level of mitigation;
- ALARP—as low as reasonably practical, often expressed in societal norms, i.e. acceptable occurrence rate of death or injury.

The facility design elements should be developed in accordance with accepted national and international standards and be based upon a fundamental understanding of the characteristics of the facility, of potential failure mechanisms and on the impacts of construction and operational issues. The selection of an appropriate design solution should be based upon a quantitative risk analysis to establish the most cost-effective risk management approach (avoidance, mitigation, contingency or risk acceptance). The severity of the risks identified will normally influence the selection of an appropriate risk-management strategy. For example, design alternatives with a very high severity risk rating should be avoided and a different strategy adopted, whereas very low severity risks might be acceptable providing that suitable mitigation measures have been designed and implemented. The philosophy of design safety is summarised in Fig. 5.1.

The level of cost uncertainty with respect to deriving the final design parameters for a MWF also needs to be balanced against the cost of refining the required design

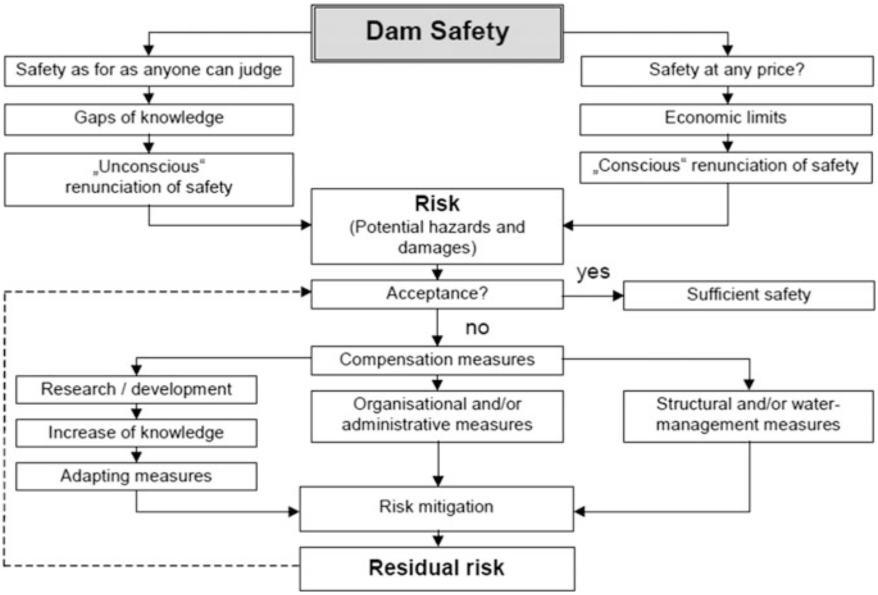


Fig. 5.1 Philosophy of dam safety (Sieber 2000)

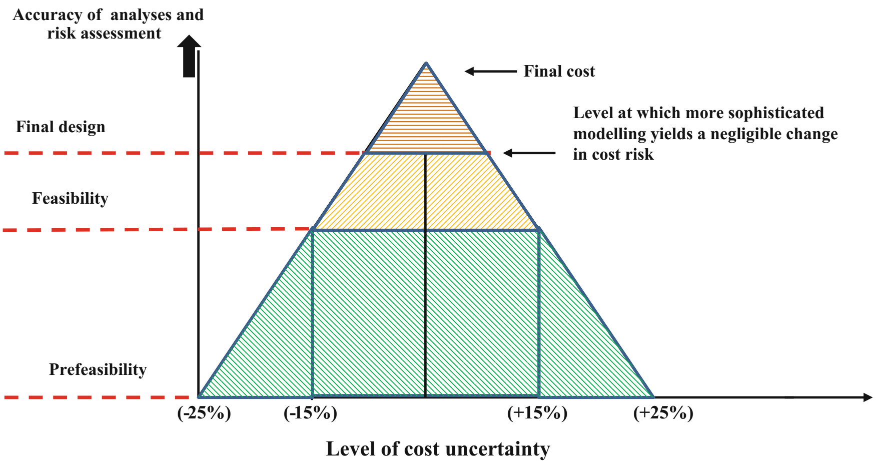


Fig. 5.2 Definition of design parameters against cost of data refinement (Cambridge 2013)

data. Designers should work towards a level of cost uncertainty at which the impact becomes negligible in relation to other design factors as shown in Fig. 5.2.

The facility design process should be fully documented and, where appropriate, be supported by a detailed engineering design register (Table 5.2). This has the benefit of ensuring that the engineering process is transparent and compliant and can be readily audited by a third party. In a typical register, strategic objectives are generally linked directly to design function, load case and material properties, and are specified for each design element. A detailed design support register is useful, not only as a guide to the structural engineering process, but as a record of decision-making and should include:

- strategic objectives—functions and properties (per objective);
- design elements (per function and property);
- design criteria, engineering practice applied and key assumptions;
- identification of risks, hazards and risk severity (multiple consequences and probabilities);
- economic impact of risks and the risk response plan;
- conclusions;
- recommendations.

Though the following sections refer specifically to extractive waste, similar provisions and technical requirements will be necessary during the design of other classified waste depositories.

Table 5.2 Preliminary risk register for a MWF

Sector	Primary risk	Risk parameter	Design strategy
Mine development	Ore geology Resource	Mineralogy and alteration Tonnage and mine life	
Mine dewatering	Minewater volume	Quality Seasonality	
Mine waste rock	Mineralogy Production schedule	Geochemistry and geotechnics Quantity and rate of availability	
Ore extraction	Extraction rates Mining method	Ore dilution and contamination Geotechnics	
Ore comminution	Grind size	Geotechnics and geochemistry	
Mineral processing	Chemical alteration	Geochemistry and geotechnics	
Hydraulic fill	Slurry quality Production rates	Geotechnics and rheology Chemistry	
Mine waste management	Quantity and quality	Consistency and sources	
Effluent recycle	Quantity and quality	Metal recovery Overall minewater balance	
Closure	Long-term liability	Geotechnics and geochemistry	

5.2.3 Regulatory Requirements

Within the EU, the disposal of all extractive waste must be undertaken in strict compliance with regulations throughout operating life and beyond. The classification of both the extractive waste and of the storage facility is an overarching requirement and the process of categorising both the MWF and the extractive waste is illustrated by the flow chart given in Fig. 5.3. This regulatory flow diagram is a typical example developed by a Regulator (SEPA 2010) for the permitting and approval of a new Category A mine waste facility in Scotland. The flow chart presents the technical steps required to identify Category A or Non Category A status as well as all those necessary for ensuring compliance with the EWD, and mirrors those adopted in other EU member states. This approach, which underwrites both design and operation of the MWF, has been used as the basis for these guidelines.

The EWD applies to all extractive waste facilities as defined in Articles 2 and 3, i.e. waste rock dumps, tailings management facilities, silt lagoons and, in some jurisdictions, is referenced with respect to good practice for ash and sewage sludge lagoons. Figure 5.3 and similar national guidance documents (HMSO 2011 and

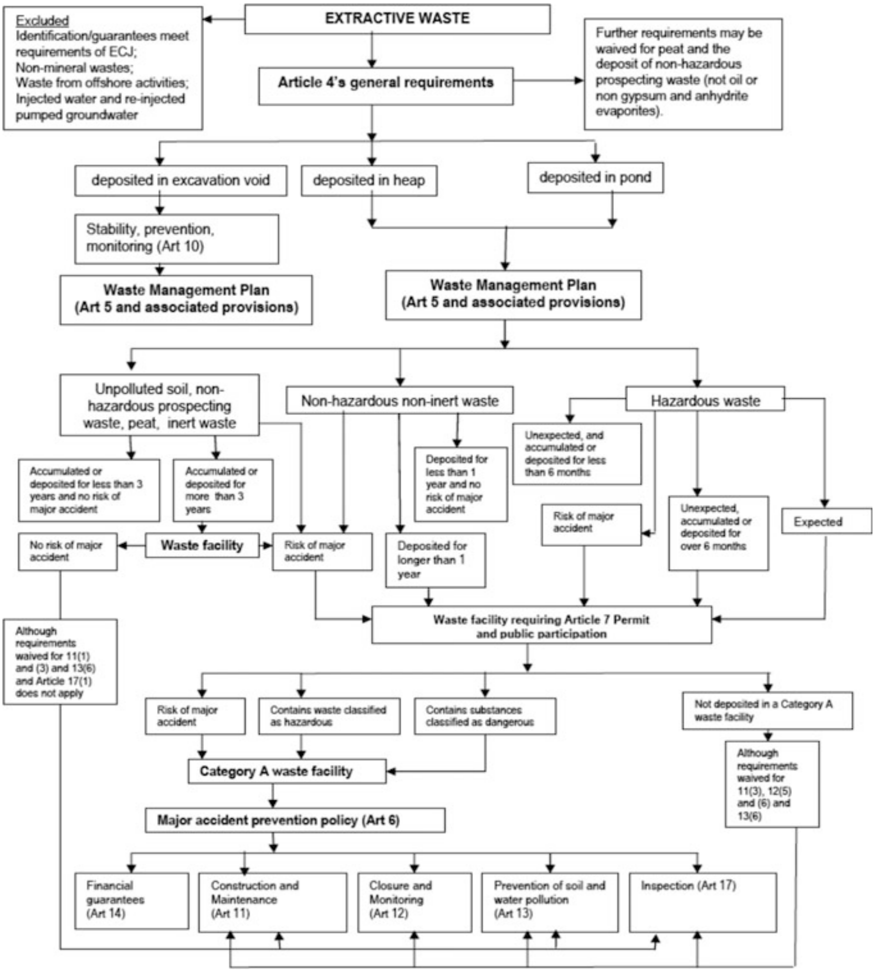


Fig. 5.3 Classification of a residue waste management facility (SEPA 2010)

SEPA 2010) recognise the importance of the categorisation process, the assessment of the hazardous nature of the extractive waste and of the risk posed by the facility in defining the MWF as either Category A or Non Category A. Of importance in the context of these guidelines are the additional design considerations necessary for a Category A facility as required by the EWD, as indicated below:

Waste categorisation
Facility categorisation
Emergency planning
Permitting (Environmental Permitting in the UK)
Competence in design and operation

Inspection
Financial guarantees
Closure

In addition, and of particular relevance to these guidelines, is that the EWD specifies that the design shall be undertaken by competent personnel, be reviewed and inspected from time-to-time and be certified by the Regulator and, as appropriate, by an independent expert in order to verify both construction standards and the ongoing stability of the facility.

5.2.4 Waste Storage Strategy

The design of a facility for the storage of hydraulically placed extractive wastes requires a corporate waste management policy against which all designs and operational standards can be developed and subsequently managed and which is in strict compliance with the prevailing regulations. Three essential requirements need to be met in order to ensure that the strategic objectives are achieved:

- waste materials must be correctly characterised, as outlined in Chap. 4, given their overriding importance in driving the facility design process;
- storage objectives must ensure optimal use of the placement environment under all operating conditions;
- the functional requirements and properties of each strategic objective must be resolved by specific design elements.

5.2.5 Waste Material Characterisation

The geotechnical properties of the waste materials to be deposited fundamentally affect the design and the performance of the disposal facility during both operation and post closure. Material characterisation as described in Chap. 4 forms a fundamental part of the pre-deposition investigation and design phase, as well as being essential during operation to ensure that the assumed parameters for the deposit are being achieved. Though for the most part the materials used for hydraulic fill have similar properties to normal geological soils, the processing, the hydraulic transportation and the geochemical characteristics may impart non-standard properties to the material both at particulate and mass deposition level.

Characterisation of the waste involves geotechnical classification to determine both short- and long-term physical properties, as well as separate geochemical assessment in order to identify any hazardous or dangerous substances or acid generation potential.

5.2.6 *Establishment of Design Criteria*

The principal purpose of a confining system is the storage of the mine waste in a controlled manner for an infinite amount of time (Bjelkevik 2005) and the design of the facility must therefore consider the following:

- the existence of adequate capacity to store not only the particulate waste but also process waters and any run-off from precipitation on the mine site and, potentially, on the upstream catchment. The importance of waste storage capacity lies in the fact that it controls the quantity of mineral reserves which can be extracted;
- the local topography, geology, hydrology and climate, as well as the characteristics of the waste material to be stored, which will determine the site, type and available volume of the depository;
- the nature of any confining structure or dam required to contain the waste and the available sources of construction material, local borrow materials, the mine waste product or combination of both natural and waste materials;
- the method for constructing the confining embankments and placing the hydraulic fill into the facility in the context of its configuration, recognising that in comparison with water retention dams, which are often built to the final height in one operation, there is the need for staged raising as the extractive or process activities proceed and the volume stored in the impoundment increases.

The methodology adopted for raising the embankments and for hydraulic placement, as well as the waste characteristics, may change during the operation of the depository, often with radical impacts on both the design and the operation process.

5.2.6.1 Design Elements

A MWF for the retention and long-term storage of hydraulically-placed extractive waste would normally comprise one or more confining embankments, dependent on the configuration of the depository, together with all necessary infrastructure to enable safe and efficient management of disposal operations, including emergency spillways, decant and river diversion structures, hydraulic fill and return water pipelines and seepage control systems. Additional impoundments comprising further embankment dams may be required on an extractive site to provide emergency process water supply or for control of seepage flows and site runoff. Figure 5.4 shows the general arrangement of the confining embankments and associated infrastructure at the Instalação de Resíduos do Cerro do Lobo MWF (IRCL) at the Minas de Neves Corvo in southern Portugal. This facility includes the following principal features:

- main confining embankment and seven saddle dams at topographic lows;
- emergency spillway;
- flood diversion impoundments and stream diversion system;
- industrial water storage and return and recycle water system;
- seepage management, control sumps and recycle pumps;
- pollution control dams.

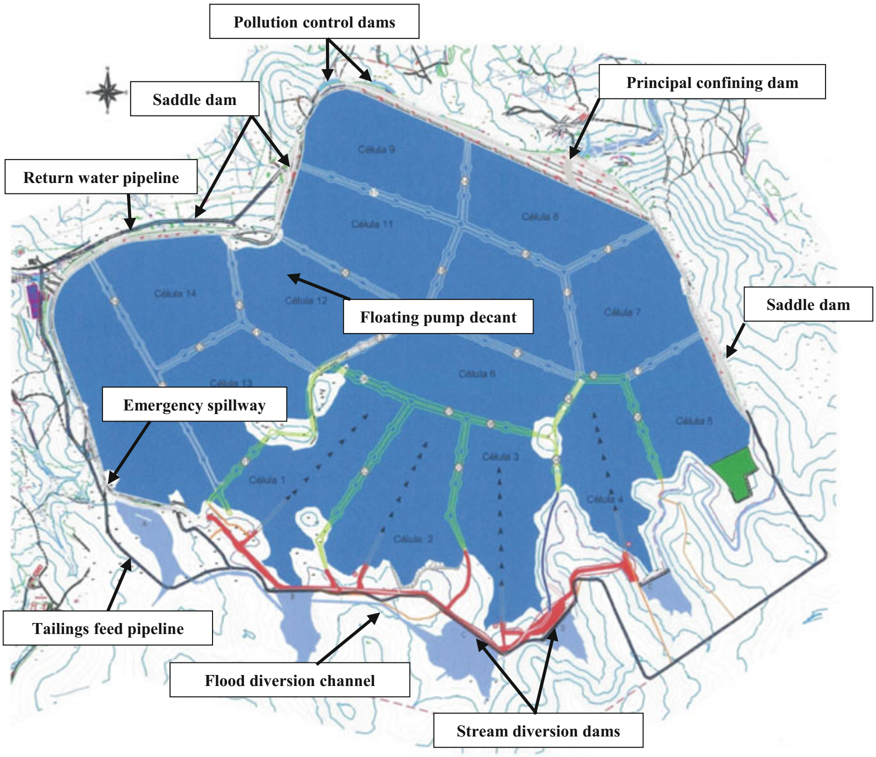


Fig. 5.4 Generalised layout of the IRCL MWF, Portugal

5.2.6.2 Design Parameters

The MWF requires adequate capacity to store not only the extractive waste but also process waters and direct rainfall falling within the impoundment area. The confining embankment should therefore be sited to ensure sufficient storage volume, and be robustly designed to prevent any failure or long-term deterioration which might lead to an untoward release of the waste product or of the contained process water. The MWF should include all necessary infrastructure to enable the facility to be operated and closed in accordance with the design parameters and with both planning and environmental constraints. The MWF and all such infrastructure should be designed and constructed in accordance with statutory requirements, i.e. with both national and international standards and with good practice in order to store the extractive wastes and process waters in safety. The design principles should be developed by the designer and reviewed at each development phase (Table 5.3) in close consultation with the owner's independent engineer (EC 2012) (Fig. 5.5), who will provide certification of the final design to the regulator and confirm that construction and operation is proceeding in accordance with the design. In particular, all material parameters, factors of safety and stability and flood assessments need to be compliant with good practice and to meet standard national and international criteria for such facilities. The design and construction of the embankments should be subject to regular (at minimum annual independent review), due to the dynamic nature of a MWF, in order to confirm the stability of the embankments and the ongoing validity of the risk assessments together with standards of construction and maintenance.

Compared with water-retention dams (McLeod 2003), which are often built to the final height in one stage, mine waste confining embankments are not only raised in a number of lifts as mining activities proceed but the methodology for raising them, for hydraulic placement, and even the waste characteristics, may change during the operational period. The facility therefore needs to meet all necessary design requirements at each staged raise and the risk analysis should include the possibility that materials, as well as the surrounding conditions (including extreme hydrological or seismic events), may change during the operating life, as shown in Table 5.4. The basis of the design and risk assessment should also be reviewed regularly throughout the life of the project and be updated by the designer as appropriate.

A MWF is required to store the wastes generated over the mine life and needs to accommodate appropriate statutory and legislative obligations, as well as those of local planning, with respect to the safe, efficient and environmentally acceptable disposal of the waste products emanating from the extractive waste project. The materials for permanent storage may comprise tailings, silts, mine waste rock and other process residues which could potentially be produced during the project life. The storage facility, therefore, must meet the following requirements:

- design, construction, operation and closure in accordance with the prevailing Directives and standards of good practice;
- disposal to ensure the settlement and consolidation of the finest particles and the maintenance of satisfactory supernatant quality;
- the control and recycling into the facility of all seepages and potentially-contaminated waters;
- the arrangement of the facility to suit the requirements of the process plant, of land availability, of the economics of the project, of environmental constraints and of operational flexibility throughout its design life;
- the retention or over-spilling in safety of all surface water flood flows after project closure.

In addition, the facility must be designed to operate safely and efficiently throughout the mine life, and to resist effectively all potentially destabilising factors. The hazardous elements of such events, together with the associated consequences, should be addressed in the design of the facility, and appropriate factors of safety adopted.

Table 5.3 Waste facility development risk assessment phases

Regulatory	Project phasing	Design/risk assessment phases
Project initiation		Preliminary financial assessment
Pre-development	Pre-feasibility study	Preliminary project risk assessment
	Conceptual engineering	Qualitative assessment of preferred option Preliminary environmental risk ranking Permitting risk assessment
Permitting	Feasibility study	Phase I quantitative risk assessment Definition of environmental risk and mitigation Geotechnical and geochemical risk assessment
	Final design Project approval	Phase II quantitative risk assessment Environmental design risk assessment and mitigation strategy Engineering design risk assessment and mitigation strategy Failure risk assessment for emergency planning Independent review of risk evaluation and mitigation strategy
	Pre-deposition Operating permit	Risk management through construction CQA Independent overview of risk management and CQA
Compliance	Operation Annual compliance reporting	Risk management through strict compliance with design Ongoing review of risks through facility inspection and monitoring Regular updating of operating and maintenance manual Ongoing waste and facility characterisation Regular review of emergency and closure planning Annual independent design overview, inspection and reporting
Closure	Active closure Compliance reporting	Confirmatory engineering stability risk assessment Finalisation of closure plan, design risk assessment and mitigation Confirmatory assessment of rehabilitation strategy Independent closure plan overview, inspection and reporting
	Passive closure Final compliance reporting	Risk management through closure completion CQA Ongoing review of risks through facility inspection and monitoring Long-term performance review through independent inspection Independent inspection and sign-off

Table 5.4 Risk summary for all design stages (Adam et al. 2004)

Event	Typical risk assessment for a MWF		Typical applicable UK standards
Natural event	*Hazard*	*Consequence*	Ref. CIRIA report, risk management for UK reservoirs
Seismic event	Catastrophic failure Untoward discharge	Extreme loss of life Environmental damage	BRE report "An engineering guide to seismic risk to dams in the UK"
Extreme flood	Catastrophic failure Untoward discharge	Extreme loss of life Environmental damage	ICE report "floods and reservoir safety" Recent Defra guidance EU directives
Unknown geology	Progressive failure Uncontrolled release	Possible environmental damage and loss of life	BRE "An engineering guide to the safety of embankment dams in the UK" BS5930/Eurocode 7 ICOLD Bulletins
Upstream instability	Overtopping Untoward release	Extreme loss of life Environmental damage	ICE report "floods and reservoir safety" Recent Defra guidance ICOLD bulletins Eurocode 7
External event	*Hazard*	*Consequence*	
War or sabotage	Progressive failure Uncontrolled release	Possible environmental damage and loss of life	ICOLD bulletins
Internal event	*Hazard*	*Consequence*	
Internal instability	Progressive failure Uncontrolled release	Possible environmental damage	BRE "An engineering guide to the safety of embankment dams in the UK" ICOLD bulletins Eurocode 7
Operational fault	Catastrophic failure Untoward discharge	Extreme loss of life Environmental damage	HSE guidance ACOP ICOLD bulletins

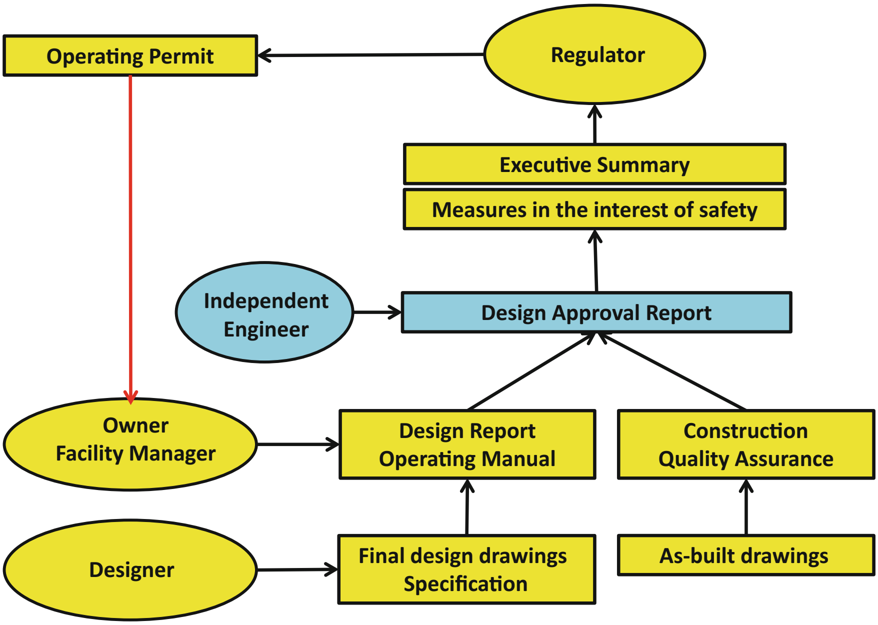


Fig. 5.5 Review and approval process for a MWF (Cambridge 2015)

5.2.7 *Design Risk Assessment*

The design process should involve the identification of all potential hazards, not only during operation but post closure as well. This enables the designer to mitigate the risks at each stage of the facility during the design and construction process. The key risks which must be addressed in addition to those normally associated with dam design are the geotechnical and geochemical characteristics of the extractive waste, the site water balance, the local hydrology, the robustness of the design under seismic loading and the potential for untoward releases, as well as those posed as a result of poor management or operation. The risk to life and to the downstream environment must be identified in order to assess the risk category of the facility and thus allow appropriate factors of safety to be used in the design (Sect. 5.6). Again, these risk assessments must include an evaluation of the potential for long-term geotechnical and geochemical deterioration of the materials stored in the depository or used to confine the waste product. The stability, hydrological and seismological design assessments, in particular, must be robust for each phase of dam raise construction.

The assessment of the design and construction risks benefits from a review of case histories of similar structures and, in particular, of failures. Such an assessment of the frequency of the dominant failure modes for MWFs was undertaken by the tailings dam sub-committee of ICOLD and is summarised in Fig. 5.6. These data provide a useful starting point for an overall risk assessment of a MWF.

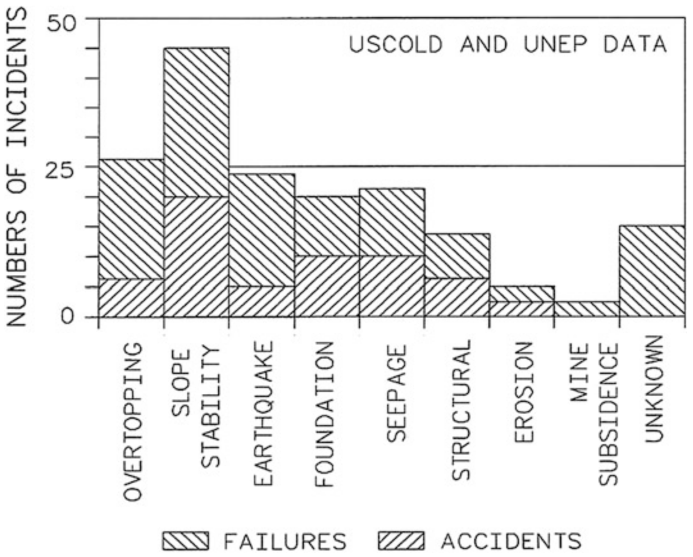


Fig. 5.6 Summary of historic tailings dam incidents (ICOLD 2001)

ICOLD Bulletin 121 concluded that "attention at the design stage to the critical issues that can affect the long term safety of a tailings facility will pay dividends throughout the life of the facility". The Bulletin provided a list of the primary features affecting the design of a tailings disposal facility and, in particular, those concerning the stability of the confining embankment, namely:

- detailed foundation conditions;
- ultimate height and angle of the outer slope;
- the rate of deposition and the detailed properties of the tailings;
- provision of adequate drainage;
- seismic influences;
- control of hydrology to avoid overtopping;
- control of the phreatic surface within the main embankment body to prevent high pressures.

The identification and assessment of the risks associated with the implementation of a MWF is a fundamental phase in the design process, and should provide the basis for the mitigating measures required in order to ensure that the construction, operation and the reclamation of the project site after the cessation of activities are effected in a safe and environmentally acceptable manner. A simplistic assessment of potential failure mechanisms is shown in Table 5.5, the elements included being

Table 5.5 MWF risk assessment

Failure mode	Consequence	Mitigation measures
Foundation instability	Failure of embankment leading to loss of production and discharges downstream, with potentially severe consequences for danger to life, environmental impact and corporate reputation	Detailed site investigation and laboratory study of underlying geology and foundation zone, leading to stability assessment with factors of safety exceeding minimum international and national criteria
Embankment overtopping	Failure of embankment leading to loss of production and discharges downstream, with potentially severe consequences for danger to life, environmental impact and corporate reputation	Spillway designed to pass or store routed PMF in safety at all stages of construction
Embankment stability	Failure of embankment leading to loss of production and discharges downstream, with potentially severe consequences for danger to life, environmental impact and corporate reputation	Detailed site investigation and laboratory study of construction materials, together with ongoing CQA, leading to stability assessment with factors of safety exceeding minimum international and national criteria
Seismic instability	Failure of embankment leading to loss of production and discharges downstream, with potentially severe consequences for danger to life, environmental impact and corporate reputation	Adoption of national seismic and stability guidelines which exceed minimum international criteria
Uncontrolled seepage	Development of sinkholes and promotion of internal instability leading to localised failure of embankment, with potential loss of production and discharges downstream and severe consequences for environmental impact and corporate reputation	Design of internal drainage control system to cater for seepage volumes at all stages of deposition, with suitable factors of safety and quality control of embankment construction materials to ensure internal filter relationships
Appurtenant structures	Potential for piping failure and promotion of internal instability leading to localised failure of embankment, potentially to loss of production and discharges downstream and to severe consequences for environmental impact and corporate reputation	Decant and other internal structures designed to accommodate total embankment stresses, with built-in redundancy and full instrumentation
Erosion	Potential for erosion of embankment and spillway walls as well as untoward discharge of tailings and process waters, potentially leading to loss of production and discharges downstream with severe	All embankment surfaces to be placed at slopes which encourage controlled runoff and all vulnerable pipelines to be instrumented to enable untoward leakage and discharges to be identified. No

(continued)

Table 5.5 (continued)

Failure mode	Consequence	Mitigation measures
	consequences for environmental impact and corporate reputation	pressurised pipelines to be laid on embankment surfaces
Mine subsidence	Potential for settlement beneath embankment walls and instability leading to localised failure and untoward discharge of tailings and process waters, potentially to loss of production and discharges downstream with severe consequences for environmental impact and corporate reputation	Detailed site investigation and historical research of old workings, leading to design of suitable stabilising measures in accordance with national guidance for treatment of underground voids, adits and shafts

a direct reflection of the principal historic failure modes for mine waste facilities. This table provides outline guidance as to the modes to be considered in assessing the overall risks associated with a facility to confirm that the proposed mitigation measures are in line with good practice.

5.2.8 Risk Mitigation Strategy

Having reviewed any relevant historical precedents and assessed the potential risks and impacts associated with the facility it is necessary to demonstrate how these are being (or should be) mitigated. The design-mitigating features should be developed on the basis that loss of life or risk of serious injury to either operators or those in the downstream catchment is not acceptable and that there should be no net loss of environmental or social assets, i.e. community, land or habitat quantity or quality. The design and construction must therefore clearly demonstrate that the facility include mitigation elements for all potential risks in accordance with the following hierarchy:

- avoidance—potential risks or impacts being removed or avoided altogether by the design and by the selection of technology and/or location;
- reduction—the risks or impacts being reduced or minimised where avoidance is not possible;
- restoration—mitigation by restoration, translocation, rehabilitation or clean-up where residual impacts are inevitable but reversible;
- offset—some form of offset or compensation for the residual impacts being applied, usually provided as a long-term replacement for any assets lost where other mitigation strategies are either not practicable or acceptable.

Risk assessment is an ongoing process during the development and implementation of a mine project, commencing at the conceptual design stage with the selection of site location and process circuit. It is further developed during the basic and detailed engineering stages, during the operation and upgrading of the installed facilities, and is concluded during the implementation and monitoring of the closure plan in the post-operation period. Risks can change as the project develops and therefore the corresponding measures for their prevention and mitigation may need to be modified in order to reduce risk exposure and achieve the specified structural or environmental objectives. The basis of the design risk assessment should be reviewed regularly and verified or updated by an independent engineer (see Chap. 7) during the life of the project.

The risk assessment process requires the systematic application of management policies and procedures in order to identify, assess, control, mitigate and monitor risk during the whole life-cycle of a project (Adam et al. 2004). Risk analysis is unique to each project but the basic logic is similar, i.e. identification of the potential risk, classification of the level of the risk which may occur in order to understand if it is high or low priority, and planning for remediation and/or mitigation in order to lower the potential for the event to occur. Reducing hazard potential should be achieved through design, monitoring and remediation and the accompanying risk analysis should include the possibility that the surrounding conditions, such as land use, demography or climate, may change. This risk analysis needs to be reviewed and updated regularly to take account of any such changes, particularly those related to extreme hydrological or seismic parameters (Cambridge and Drielsma 2007) and should make allowance for the impact of climate change. A generic flow path for a typical risk assessment is illustrated in Table 5.5 with an example design assessment for a MWF in a location with well-developed engineering standards being shown in Table 5.6.

The risk assessment methodology for MWFs adopted under the EWD is based on consequence, a procedure well-accepted throughout the EU for water supply reservoirs. Dam failures (total or partial), as well as incidents related to the stability of a MWF, may be caused by a range of faults. Particular issues associated with a MWF relate to the use of the extractive waste for dam construction and require both the analysis of risk and the characterisation objectives to be aligned to ensure that all factors which could potentially lead to dam failure are addressed. The characterisation of a waste facility as Category A imposes a number of strict requirements on both owner and the regulator, including specific provisions for the waste management and emergency planning as well as for closure. It is noted that these constraints do not extend significantly beyond those already required for compliance with good practice and, particularly, with ICOLD and other national guidelines. The assessment of the proposed design, construction and operation parameters should be undertaken against such guidelines, noting in particular the criteria summarised in Table 5.7 in order in order to confirm the appropriateness of the design proposals and of the associated mitigation measures. Further, the mitigation measures to be incorporated into the design should reduce the overall risk of a significant failure event during construction or operation to an extremely low level.

Table 5.6 Example of the principal embankment design assessments from the UK

Design assessment	Description
Embankment stability	Embankment at all stages designed in accordance with national, international and ICOLD guidance Minimum long-term factor of safety f > 1.5 Minimum short-term or dynamic factor of safety f > 1.1
Hydrological considerations during design and construction	Designed in accordance with current national guidance for flood standards for dams and for the identified risk category (ICE 2015a, b)
	The "safety check flood", often made equal to the probable maximum flood or in some jurisdictions to the 10,000-year event. It is considered acceptable practice for the crest structure, all waterways and the energy dissipater to be on the verge of failure, but to exhibit marginally safe performance characteristics for this flood condition
	The "design flood", strictly representing the inflow which must be discharged under normal conditions with a safety margin provided by the freeboard. It is usually taken as a percentage of PMF or a flood with a given probability of exceedance (such as 1:100, 1:1000)
Seismic design considerations	The stability assessment includes seismic design considerations in accordance with national and international standards and guidelines (ICOLD 1995 and BRE 1991, 1999), as follows: Maximum credible earthquake—when subjected to the MCE, damage is limited and no catastrophic failure will occur
Embankment stability at closure	At closure, the final embankment profile complies with EU and ICOLD sustainability guidelines (ICOLD 2011)

Table 5.7 Design risk criteria to prevent untoward failure (ICOLD 1995, 2001)

Component	Design questions
Dam and foundations	Has the dam been designed by competent engineers, with due regard for foundation condition, internal drainage, slope stability, seismic loading and contaminant containment? Are tailings or cyclone sand to be used for construction and has the structure been assessed with the same rigour as an earth/rockfill dam? Is the dam instrumented and/or monitored so as to reveal any abnormal behaviour?
Waterways	Are the decant systems secure and have all pipes through the dam or foundation been adequately sealed? Is there sufficient flood storage capacity and are spillways and/or diversions adequate for the design floods? Are there any hazards associated with the tailings delivery lines and water reclaim lines?
Closure	Has the structure been designed to accommodate potential changes in operating conditions over the closure period, e.g. erosion, floods, sediment, inflows or natural landslides?

5.2.9 Adoption of 'Good Practice' Standards

As previously described, the fundamental principles of good practice for a MWF are underpinned by a risk-based approach to planning, design, construction, operation and closure. Using a risk-based design approach to generate an understanding of all potential failure mechanisms which might occur within the MWF facilitates the adoption of appropriate design solutions in order to achieve the most cost-effective risk management approach (avoidance, mitigation, contingency or risk acceptance) and to define the optimum operating parameters.

Adoption of good practice project management standards enable:

- determination of the optimum system for construction, operation and closure of the facility;
- adoption of appropriate standards (CQA) throughout each stage of development of the MWF;
- all risks to be considered and suitable mitigating measures incorporated into the design, operation and management.

5.3 MWF Design Considerations

The materials for permanent storage may comprise, in addition to hydraulic fill, mine waste rock and other treatment residues which could potentially be produced during the project life. The associated MWF must therefore meet the following requirements:

- design, construction, operation and closure in accordance with prevailing Directives, national standards and good practice;
- disposal to ensure the settlement and consolidation of the finest particles and the maintenance of satisfactory supernatant quality;
- the retention or over-spilling in safety of all surface water flood flows both during and after project closure;
- the control and recycling into the facility of all local seepages and potentially-contaminated waters;
- the arrangement of the facility to suit the requirements of the process plant, land availability, economics of the project, environmental constraints and of operational flexibility throughout its design life.

In addition, the facility must be designed to operate safely and efficiently throughout the mine life, and to resist effectively all potentially destabilising factors. The hazardous elements of such events, together with the associated consequences, should be addressed in the design of the facility, for which appropriate factors of safety should be assigned.

Since the extractive waste generated during mine life needs to be confined behind an embankment dam to suit engineering and environmental requirements, the location of the embankment has to be chosen to provide robust waste storage capacity, an acceptable dam fill and reservoir storage ratio and suit local topography, geology and geotechnical conditions. The main confining embankment should be developed using locally-available materials where possible, either from borrow or, subject to suitability, mine waste and the most cost-effective cross-section and construction method chosen to suit the site. The facility should be constructed on competent foundations proved by geological mapping and intrusive geotechnical exploration using embankment fill materials, both structural and lining, which meet the needs of stability and environmental performance. All materials need to be proven geochemically and geotechnically to provide a robust design satisfying environmental and stability criteria under both static and dynamic loading.

5.3.1 Design Basis

The design process therefore involves the identification of all potential hazards, not only during operation but post closure as well. This enables the designer to mitigate the risk during the design and construction process. The key risks which should be addressed in addition to those normally associated with dam design are the geotechnical and geochemical characteristics of the mine waste, the site water balance, the local hydrology and the robustness of the design under seismic loading. The potential consequences to life and the environment downstream should be identified in order to assess the risk category of the facility, thus enabling appropriate factors of safety to be used in the design. Again, these risk assessments should include an evaluation of the potential for long-term geotechnical and geochemical deterioration of the materials stored in the depository or used to confine the waste product. The assessments must be robust for each phase of dam raise and construction.

In some EU Member States national regulations require that storage facilities be designed, constructed and operated in accordance with good international practice and that the same risk categories be applied to such items as flood design, seismic criteria and to emergency planning as used for large raised reservoirs (Cambridge 2008a, b). This generally indicates that the MWF requires special consideration for these design elements and that the confining embankment and appurtenant works should be designed by an experienced competent engineer in accordance with both national and international standards and to a design brief agreed with the owner's independent engineer.

The key design factors to be studied in detail during the final design stage are summarised below.

5.3.2 Site Selection Considerations

Site selection for a MWF is dependent on its location in relation to the process plant and to the economics of transportation and deposition, as well to local conditions such as topography, geology and climate, environment and social implications in the specific context of the geotechnical and geochemical characteristics of the hydraulic fill product. A simple risk assessment and site screening process based on preliminary site reconnaissance and a desk study for evaluating the initial MWF site and for focusing the initial detailed investigations is shown in Table 5.8. Such an assessment using a simplistic but effective ranking from 1 (unacceptable) to 5 (acceptable) enables preliminary screening of all available sites, the elimination of unacceptable locations and a more cost-effective investigation of the optimum site and configuration.

The preliminary screening enables the development of the optimal option/s for the MWF for further investigative works. This phase should entail a detailed investigation programme, enabling consideration of the chosen site/sites in more detail, and provide not only the pre-feasibility assessment but an evaluation of the costs of developing a particular site in terms of construction, operation, closure and

Table 5.8 Typical initial site risk assessment for a mine waste facility

Project risks	Weighting	Ranking (1–5)				
		Site A	Site B	Site C	Site D	Site E
Topographic suitability, i.e. dam wall volume and waste storage ratio						
Geological and geotechnical site suitability						
Seismic considerations						
Hydrology under both extreme drought and flood conditions						
Mine site water balance						
Environmental considerations (general)						
Environmental considerations (vulnerability of downstream catchment)						
Site access and mine site location						
Climate						
Total score						
Possible additional screening elements						
Waste characterisation						
Facility characterisation						
Historic mine workings						

environmental and social mitigation. Given the current legislative environment, the cost of permitting the particular site should also be assessed.

The site chosen for the feasibility study (DFS or BFS as appropriate) should be justified during the final design phase against an appropriate balance between engineering, operational, economic and environmental criteria, taking into account the local regulatory framework. The options will have considered the following, set against the known material and site parameters:

- site location in relation to the risks and potential impacts, the transportation distance, engineering requirements and construction costs;
- extractive metallurgical process and technology options in relation to the physical and chemical behaviour of the fill itself, as well as to the constituents of the process water storage and return system;
- construction of the MWF in relation to the properties of the engineered fill, the configuration and zoning of the confining embankment and the ongoing containment of seepage through the embankment and base of the facility;
- deposition of the hydraulic fill in relation to the properties of the tailings slurry, variations in feed characteristics, sedimentation and consolidation rates;
- control of all potential releases to the downstream environment with respect to seepage, flood events and airborne emissions.

The adoption of the optimum site will enable a BFS and permitting design to be prepared for a MWF based on the chosen location. The design detail to be provided for permitting will be dependent on the specific regulatory environment but the documentation to be submitted should present the intended outline design of the MWF and the supporting data be suitably robust such that the regulator can have confidence in the overall design, in the construction system and in the environmental mitigation measures proposed.

Receipt of a permit enables the final design of the pre-deposition works, which should address not only the detailed engineering for this phase but its interaction with the final construction details for each element of the facility and their phasing. During the pre-deposition works the designer should prepare the detailed methods of construction and associated quality assurance procedures together with the Operating and Maintenance Manual. This Manual should specify not only the ongoing quality assurance procedures and control systems for the staged construction works but also detail the operation of the facility, the control and management of the hydraulic disposal system and industrial water circuit, and the instrumentation and inspection requirements.

These processes and procedures should apply to the development of a MWF proposed for a new site as well as to the extension of an existing facility to which the same engineering criteria and regulations will apply.

5.3.3 Material Properties

The site investigation and other laboratory testwork should be undertaken in order to indicate that all potential construction materials have suitable properties for inclusion in the confining embankment. It should be recognised that the characteristics of any extractive waste materials used to construct the MWF, and also of the hydraulic fill deposited, may change during the operational period, particularly if extraction operations progress from an oxide to an unaltered ore body. The design of the confining embankment and the associated construction practices should be suitable to enable such changes to be accommodated without compromising safety. Similarly, the storage characteristics and the staged design should be robust enough to meet any changes in extractive waste production rates.

The construction of the confining embankment, though following normal geotechnical design procedures, may be undertaken using a wider range of techniques and engineered materials than is common for water supply dams. The confining embankment may be constructed from locally won borrow materials, from waste rock derived from the mineral extraction operation or from the finer waste materials (tailings) themselves. In each case the intrinsic geotechnical and geochemical properties of the materials to be used must be characterised (see Chap. 4) and the design prepared accordingly, using recognised good practice. The storage facility, and particularly the confining embankment, must be configured in the knowledge that materials available for construction and the properties of the waste product may change during the life of the facility, and thus a degree of flexibility must be incorporated into the design.

5.3.4 Confining Embankment

The confining embankment should include a main structural section comprised of engineered mine waste or imported fill, together with the necessary filter zones, underdrains and seepage collection systems. The earthworks used for the construction of the confining embankment should be comprised of engineered fill placed to an appropriate specification to suit the properties of the fill materials. The material gradings should be checked for compatibility and be based on international standards for filter design (Sherard et al. 1984), such as the following ratio:

$$D_{15f}/D_{85s} <= 5$$

where D_{15f} is the grain size of the filter material at 15% passing.

where D_{85s} is the grain size of the base soil at 85% passing.

The compatibility criteria should be applied throughout the full embankment section including, for a MWF, the tailings deposition zone. The site investigation and laboratory testing should therefore assess the available embankment fill materials and determine and define the following:

- the full range of grading characteristics of all engineered and hydraulic fills, including both pre- and post-compaction;
- the extremes for each material grading;
- the grading and filter material selection criteria, ensuring full compliance with the specified compatibility;
- the CQA testing protocols, frequencies and allowable failure rates (non-compliances);
- the failure criteria and remedial actions.

All the above must be clearly specified in the earthworks specification and construction procedures.

The seepage control zones should be designed to ensure the effective capture of embankment and extractive waste seepages. The system should collect and control seepages, and recycle these either via settlement ponds or through separate pump and return arrangements. The main embankment seepage system should control the lateral movement of interstitial water through the structure into a basal collection drain via engineered filter zones, thus enabling all releases to be controlled and recycled back to the main reservoir or discharged downstream as appropriate.

At closure, the rate of seepage from the deposit and the confining embankment reporting to the downstream collection system should reduce, particularly once the reservoir (surface water) has been removed. Ultimately, the water reporting to the seepage control system in a well-engineered facility will comprise runoff only. Experience from historical tailings disposal facilities has shown that seepage control during disposal can lead to effective drainage of the mine wastes and to a decline in the volume reporting to the downstream outlet within a few years of cessation of mining operations (Cambridge 2004). The rate of this decline is generally enhanced by the early landscaping of the upper surface of the depository in order to limit infiltration and water migration through the deposit.

5.3.4.1 Static Stability

The stability of the main embankment and any saddle dams should be assessed for a range of conditions, and the design of each stage of construction reviewed to ensure the safety of the confining structures at all times during the development. Material parameters, partial factors of safety and the stability assessment should be compliant with good practice and meet standard international and national criteria for such facilities. The overall stability should be calculated using industry-standard software, and include consideration of both normal and extreme conditions as well as the range of "what-ifs?" defined from the risk assessment. In summary, competent stability analyses for embankment design depend on the following:

- selection of conservative baseline soil parameters (characteristic values);
- identification of all potential failure conditions under all operating scenarios;
- identification of all potential failure mechanisms both upstream and downstream;

- review of soil parameters for each condition, i.e. drained or undrained and post-liquefaction;
- review of stability algorithm, with subsequent validation for the proposed analyses;
- establishment of a critical stability verification system such as hand calculations or rule of thumb;
- review of stability results for consistency;
- future-proofing of records of analyses.

It is noted that if the project is to be independently reviewed and approved, the brief for the stability analyses should be agreed with the review engineer in advance.

Typical static load cases for the stability assessment should consider the following:

- unexpected geological conditions in the foundations, such as the presence of:
  - underlying weak strata
  - historical surface and deep mine workings
  - adverse faults and fractures in the underlying geology
  - adverse hydrogeological conditions
- induced instability in the upstream catchment from:
  - natural faults and fractures in valley slopes
  - rising storage levels and inundation of natural slopes
  - rising storage levels and inundation of upstream rock dumps with the storage area
- sensitivity of embankment stability at all construction stages to:
  - changes in material properties
  - the range of operating and flood storage reservoir levels
  - adverse tailings or water storage conditions
  - the implications arising from:
    - failure of the drainage/filter system (embankment drains-blocked analysis)
    - blocked underdrains (foundation drains-blocked analysis)
  - poor construction practices leading to:
    - non-compliant fill materials
    - loss of material compatibility
    - missing filter zones
    - untoward stratification of compliant and non-compliant fill
  - poor disposal management practices leading to:
    - loss of reservoir control
    - inadequate mine waste for embankment construction purposes.

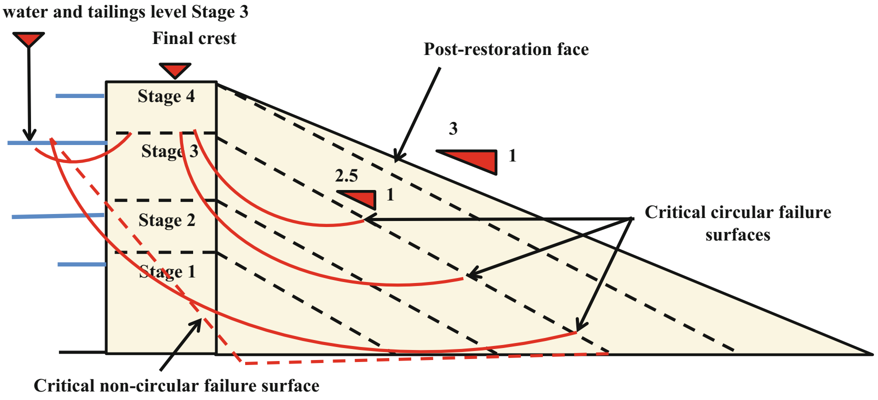


Fig. 5.7 Typical staged stability analysis

Further, the stability analyses should consider not only the highest and steepest cross-section with failure surfaces emerging at the embankment toe but also those emerging at higher elevations in order to ensure that the critical section can be identified (Fig. 5.7). The stability analyses should be completed for each critical section for the main embankment and saddle dams and both upstream and downstream failure surfaces should be considered. It is evident that the load cases specified above are not comprehensive due to the site-specific nature of embankment design and therefore some conditions may not need to be analysed in detail but may be addressed by inspection. However, all load cases considered must appear in the design register and the mitigation, or indeed design analysis, be referenced accordingly as per the example in Table 5.9.

5.3.4.2 Dynamic Stability (Seismicity)

As all mine waste facility sites should be considered to be located in seismically active regions, appropriate seismic codes need to be adopted during the design of a MWF embankment. These codes should be compliant with accepted national or international best practice and involve the identification of the Maximum Credible Earthquake (MCE) for the site, enabling the adoption of appropriate dynamic design parameters. Though determination of the Operating Base Event (OBE) is usually considered for water supply dams it is not generally deemed to be appropriate for a MWF due to the staged nature of construction and the consequences of failure associated with such structures. The materials to be included in the MWF

Table 5.9 Example of simplistic static stability design support register

Project stage	Failure mode	Stability analysis	Exit point	Reservoir level mOD	Storage level mOD	Phreatic surface	Soil parameters		Factor of safety
							Upper bound	*Lower bound*	
Permit	Upstream	Circular	Upstream toe			High			
						Low			
		Non-circular	Upstream toe			High			
						Low			
	Downstream	Circular	Downstream toe			High			
						Low			
		Non-circular	Downstream toe			High			
						Low			
Stage 1	Upstream	Circular	Deposition level			High			
						Low			
		Non-circular	Deposition level			High			
						Low			
	Downstream	Circular	Downstream toe			High			
						Low			
		Non-circular	Downstream toe			High			
						Low			
	Downstream	Circular	Berm level			High			
						Low			
		Non-circular	Berm level			High			
						Low			
Stage 2	The analyses should be repeated for all subsequent construction stages								

should, where appropriate, be resistant to loss of shear strength under seismic loading and appropriate factors of safety should be obtained for all embankment slopes from the dynamic analysis. The impact of seismic disturbance in the natural terrain within the MWF catchment also needs to be considered with regard to the risk of landslides, wave surge development and embankment overtopping. Both static and dynamic analyses of the valley side slopes should be included in the design approach, and appropriate factors of safety obtained. In addition, a review of both regional and local seismo-tectonics needs to be undertaken in order to identify the susceptibility of local geological formations to reactivation during an extreme seismic event. This is necessary in order to ensure, in accordance with recognised international practice for embankment dams, that possible active fault zones do not cut across, or daylight beneath, the MWF foundations. The results of the regional study should, as a matter of good practice, be incorporated into the final seismic design considerations for the embankment, thus ensuring that the facility is robust under the extreme event.

The basic seismic stability assessment should be based on current national guidance and may generate basic screening such as that shown in Table 5.10 and adopted in the UK (BRE 1991). It is noted that, though this screening was prepared for water dams, it is equally applicable to a MWF.

Using such a preliminary assessment, the MWF Hazard Category can be established and provide general guidance based on regional zoning of seismic risk

Table 5.10 Example of UK seismic classification (BRE 1991)

Parameter	Value	Classification factor	Classification criteria
Capacity (includes both water and solids)	20,000,000 m^3	4	>120,000,000 m^3 (6) <120,000,000 m^3 >1,000,000 m^3 (4) <1,000,000 m^3 >1000 m^3 (2)
Height	>45 m	6	>45 m (6) <45 m >30 m (4) <30 m >15 m (2)
Evacuation requirements (Number of persons)	1–100	4	>1000 (6) <1000> 100 (4) <100> 1 (2)
Potential downstream damage	High	8	High (12) Moderate (8) Low (4)
Total		22	
Seismic classification results	*Seismic zone*	*Seismic safety evaluation*	*Seismic design parameters*
	Zone A	Dam category III	Peak ground acceleration of 0.25 g Return period of 10,000-years

and on a generic maximum credible earthquake and peak ground acceleration against which the facility needs to be assessed. This preliminary assessment may indicate that, due to construction and location, static analyses or pseudo-static assessment are adequate. However, a more detailed seismic safety evaluation will be required if the overall height of the embankment is significant and if the cross-section incorporates materials with an elevated risk of liquefaction. Such an evaluation will necessitate inclusion of detailed geological mapping and identification of susceptible faulting, together with reference to regional or national detailed seismic databases such as those managed in the UK by the BGS. Such studies will generally need to be undertaken by specialists and will enable the peak accelerations and, in most instances, applicable accelerograms, to be derived for the Maximum Credible Earthquake (MCE) event.

The subsequent analyses may require an assessment of embankment settlement under seismic loading (Makdisi and Seed 1978; Sarma 1981; Newmark 1965) or a detailed simulation of post-event liquefaction and failure using advanced laboratory techniques and complex computational modelling of the embankment section. A more detailed review of seismic analytical methods is beyond the scope of these guidelines. However, a word of caution is appropriate regarding the use of pseudo-static analyses for stability assessments for a MWF for which the risk of seismic disturbance is elevated. The designer should ensure that the algorithm adopted in standard pseudo-static software is appropriate for assessing the stability of the MWF and that the results can be relied on to accurately reflect the performance and characteristics of the facility under seismic loading. Recommended minimum factors of safety are shown in Table 6.10.

5.3.4.3 Seepage Management and Control

The control and management of seepage through the confining structure and its foundations is fundamental to the ongoing stability of the facility. The designer must ensure that the embankment zoning is proof against uncontrolled seepages and their destabilising effects and that the risk of piping is fully mitigated. The design must reflect the importance of material compatibility in the adoption of suitable construction materials and with respect to the grading of the extractive waste. Further, it should also ensure that the necessary protective zones are robust against the risk of uncontrolled seepage, particularly where this may increase with time due to rising hydraulic gradient or deterioration of materials, either physically or geochemically induced.

The development of uncontrolled seepages through an embankment is shown in Figs. 5.8 and 5.9 which provide examples of physical and geochemical defects which may lead to structural problems in the embankment.

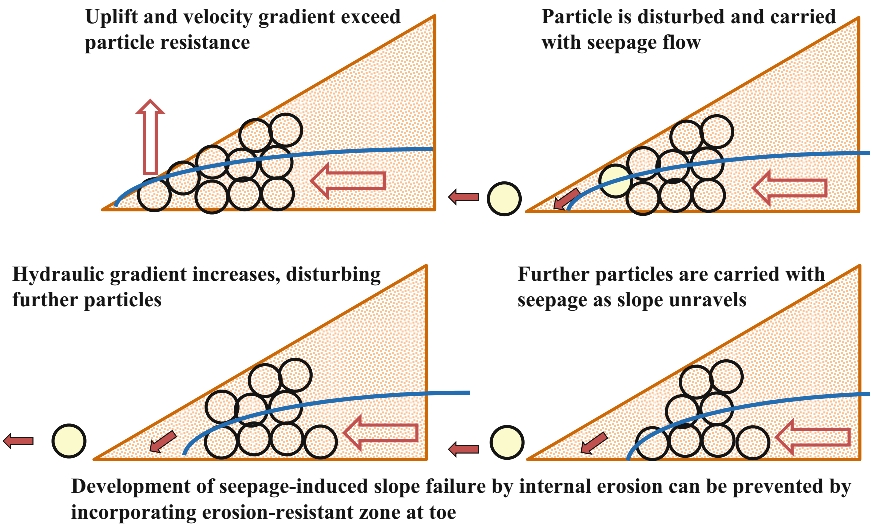


Fig. 5.8 Development of seepage-induced slope failure (Cambridge 2015)

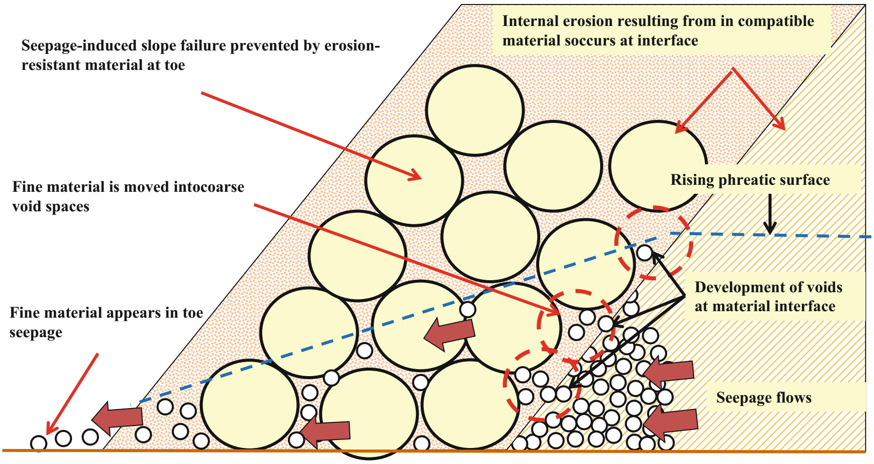


Fig. 5.9 Physically-induced seepage issues (Cambridge 2015)

Physical Seepage Control

At minimum, the effect of uncontrolled seepage will lead to localised sloughing on the face of an unprotected embankment, but in more extreme conditions may result in internal erosion (piping) and sinkhole development (Fig. 5.10) which may ultimately lead to embankment failure. The results of internal erosion in embankment dams are well-documented and the resulting catastrophic failures should be a

Fig. 5.10 Sinkhole in embankment surface caused by poor CQA on filter zone

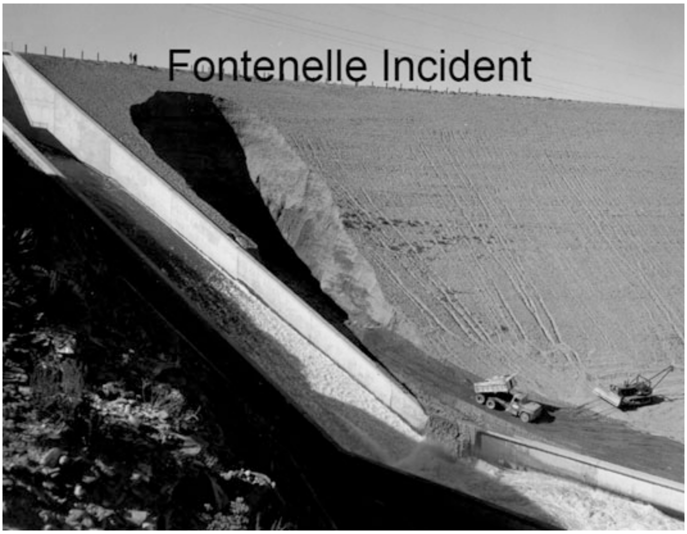


Fig. 5.11 Piping in dam face (Snorteland 2013)

warning to designers (Fig. 5.11) (Snorteland 2013). MWFs are similarly prone to piping/internal erosion, particularly where the confining embankment cross-section incorporates hydraulic fill. There are numerous instances of MWFs in Europe of poor material specification and placement control leading to internal erosion, causing sinkholes in the embankment and to their appearance at the surface of either the depository or in the embankment face. Catastrophic failures such as Bafokeng (Jennings 1979) were also in part a result of piping due to untoward reservoir elevation and lack of material protection. Failure to address such issues and to design against piping under all design circumstances and situations will lead to progressive evacuation of the structural zone and ultimately to a loss of stability, with potentially catastrophic effects. The mechanism of internal erosion and piping in dams and foundations has been studied in great detail in recent years and the findings and recommendations are included in ICOLD Bulletin 164 (ICOLD 2014).

Geochemical Seepage Control

> The reservoir's completely gone, the dam we'll see no more;
> For what they thought was H_2O was H_2SO_4
> (Cambridge 2008a, b) with apologies to chemistry teachers everywhere

The long-term performance and, especially the geotechnical and geochemical degradation of fill materials, should be factored into the design of the filter system. It is noted that many fill materials will weather in an embankment with time and the subsequent particle breakdown may render the filter design ineffective unless an adequate factor of safety has been employed.

The design risk assessment should be applied to geochemical effects as oxidation can result in hydroxides being generated and carried in the seepage through the protective zones (Cambridge 2008a, b) (Fig. 5.12). Such precipitates often comprise low-density flocs which are known to clog the pore spaces of drainage zones, again rendering them ineffective. This will result in a rising phreatic surface, with

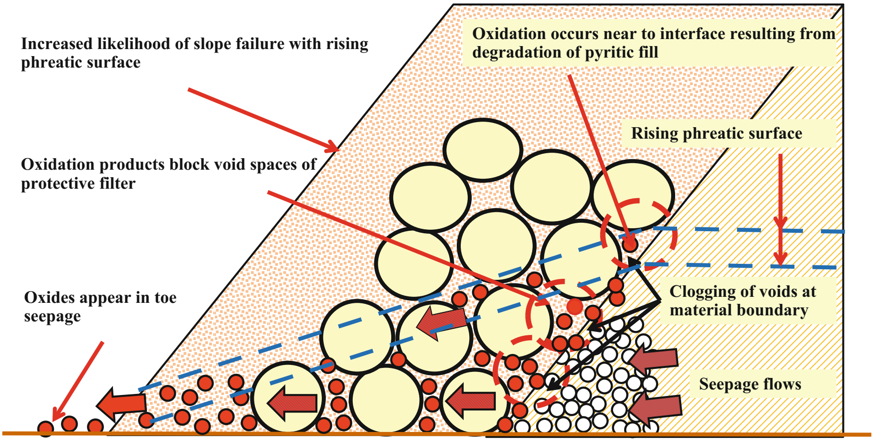


Fig. 5.12 Geochemically-induced seepage issues (Cambridge 2015)

potential destabilising consequences and severe implications for closure designs (Oliveira Toscano and Cambridge 2006).

The designer must be aware of the risks associated with the materials adopted, and ensure the following:

(i) that material gradings meet international guidance for compatibility and filter protection (Sherrard et al. 1984, ICOLD 2014);
(ii) that suitable construction quality control and management is in place to prevent out-of-specification materials being incorporated into critical embankment zones;
(iii) that compatibility checks include the extractive waste as an ongoing process to ensure that piping cannot occur;
(iv) that the adopted fill materials will not degrade physically or geochemically and render the design inadequate;
(v) that the design is proof against internal erosion under all phreatic surface, seepage and reservoir conditions;
(vi) that all filter compatibility criteria have an adequate factor of safety against failure.

5.4 Disposal Management

Hydraulic placement of the fine extractive waste and the configuration of the deposition system should be arranged to minimise transportation costs, achieve maximum storage density and efficient disposal, and ensure that closure targets are achievable. The hydraulic fill should therefore be discharged into the MWF to ensure, where appropriate:

- optimum transportation from process plant to MWF;
- integrated slurry transport and hydraulic distribution system;
- effective sedimentation in the reservoir to maximise settlement of solids;
- satisfactory physical and chemical clarification of supernatant water for return to, and re-use in, the process plant;
- management of disposal to maximise deposited densities and achieve short- and long-term effective consolidation;
- cost-effective management of the disposal system to ensure safe and efficient tailings deposition;
- controlled management of stored water to reduce the risk of untoward releases and elevated seepage levels.

The design of the deposition system requires the exploitation of the properties of the hydraulic fill, of the configuration of the depository, of the production process and of the climate to ensure cost-effective and environmentally appropriate disposal. Disposal management comprises two elements, namely hydraulic transport from the plant to the MWF and the distribution and placement system on to the surface of the depository.

5.4.1 Hydraulic Transport

The design of the deposition system generally includes the reticulation pipework from the process plant to the point of disposal. In the process of hydraulic design the key parameters of pulp density, pressure head and throughput need to be considered. The design must resolve the balance between pulp density and pumping (energy) costs, which may dictate not only the configuration of the main feedline but also of the deposition system. The design of the pipeline from plant to MWF should take account not only of the hydraulic capacity requirements but also of the abrasive nature of the tailings with respect to assessing pipe wear and longevity. These factors will be key to determining pipeline configuration, frequency and type of jointing and location of both operational and safety control valves. Further, the risk of leakage and untoward pipe-bursts should be assessed and suitable mitigating measures be taken, such as pipeline bunding and small impoundments at topographic lows being installed to prevent an uncontrolled release in the case of a joint failure or leak.

The design of the pipeline should also consider the following:

- potential extreme climatic conditions, with elevated temperatures resulting in buckling and instability in the pipeline, or freezing conditions leading to pipe fracture and leakage;
- water hammer and hydraulic surges leading to pipe fractures;
- pipe blockages cause by sedimentation in the pipeline following shutdown;
- chemical precipitation in the pipeline, particularly of gypsum, leading to reduced hydraulic capacity;
- traffic damage;
- security of the pipeline against theft of control units or untoward valve operation and other vandalism.

Finally, the design of the main feed line must consider accessibility for inspection and maintenance of the pipeline system, noting that a fracture or leak in a buried pipeline may not manifest itself for some time, potentially enabling uncontrolled releases off site.

5.4.2 Hydraulic Disposal

The choice of a hydraulic disposal system will be determined by the configuration of the MWF, the hydraulic transport infrastructure, the grading and characteristics of the tailings and ultimately by the permit conditions. In some jurisdictions in

Europe, regulatory controls have effectively specified the disposal method, resulting in owners being forced to adopt sub-aqueous deposition or filtered tailings. Storage of filtered tailings on surface does not involve hydraulic filling and is thus beyond the scope of these guidelines.

Regardless of whether sub-aqueous or sub-aerial disposal is planned, the deposition system needs to be flexible such that the natural tendency of the hydraulic fill to develop a cross-bedded laminated deposit is exploited. This will enable the elevated horizontal-to-vertical permeability ratio in the deposit to promote horizontal drainage, maximising lateral seepage, reducing saturation levels and thus increasing storage density. The extent to which this can be achieved, and the rates of consolidation, are principally dependent on the waste properties and on the confining system. The basic geotechnical characterisation of the waste forms a fundamental part of the design process and its importance in defining ongoing stability and closure should not be underestimated. Enabling effective drainage and consolidation provides a progressive improvement in overall stability as a result of the decrease in pore pressures and the corresponding rise in effective stress. The desaturation of the tailings also leads to the reduction of risk of both liquefaction and the potential for mobilisation on disturbance. Both factors further emphasise the importance of assessing the geotechnical characteristics of the hydraulic fill, not only at design phase but also during the early stages of deposition. The hydraulic deposition arrangements, together with the design and installation of internal drainage systems, need to be fully integrated to ensure that consolidation and storage density are maximised. The primary objective must be to increase surface stability with the aim of enabling early restoration, rehabilitation and landscaping at closure.

5.4.2.1 Sub-aqueous Disposal

Sub-aqueous disposal requires specific confining and disposal systems and, in particular, the requirement to confine both a lower density waste deposit and a significant reservoir, which is generally impounded against all or part of the retaining embankment. The MWF for sub-aqueous disposal necessitates a confining embankment able to retain the surface water without developing either elevated pore pressures or excessive seepage volumes. The accompanying reticulation system needs to enable the relatively even distribution of the fine waste across the reservoir basin with the aim of forming a uniform underwater surface. However, as sub-aqueous tailings achieve steeper underwater slopes, the disposal pipework must be arranged such that it can effectively distribute the tailings across the entire reservoir basin and thus be designed to be flexible. The disposal arrangements will require a perimeter manifold system which permits discharge via floating pipelines from around the perimeter of the depository. The system will need to be designed to ensure that critical velocities are maintained in the pipeline in order to prevent sedimentation and precipitation at topographic lows or where there are low gradients or pinch points. The floating pipeline will require an anchorage system which enables the outlets to be manipulated across the reservoir surface in order to minimise the extreme underwater topography of ridge and furrow, achieve a level surface to the extent practicable and maintain a minimum depth of water above the upper surface of the tailings. The design must accommodate the reduced storage density and thus increased storage volume requirements.

5.4.2.2 Sub-aerial Disposal

Maximising sub-aerial deposition by beaching across the depository is the key to effective storage, with increased pulp density implicitly leading to greater densification and the resulting physical benefits. The reticulation system, whether using open-ending, spigots, spray-bars or cyclones, must be arranged to achieve the maximum beach length compatible with water storage and return. Regular rotation of deposition points ensures the development of perimeter beaches, enabling thinner layers and thus encouraging air-drying and desiccation. Rotation also ensures control of the reservoir perimeter, improves embankment stability and prevents excessive erosion and re-deposition. In addition, as the tailings themselves may vary considerably in grain size, mineralogy and pulp density, a key function of the design is to deposit in such a way which maximises sedimentation and minimises solids return to the plant. Except for highly thickened tailings, which only generate bleed water, the minimum settling velocity of the tailings, often taken as the velocity at which 95% of the solids settle, will determine the minimum operating area of the surface water pond (Twort 1994) as follows:

$$\mathrm{A_R} = \mathrm{q_i}/\mathrm{v_{95}}$$

where:

$\mathrm{A_R}$ is the minimum reservoir area required to settle 95% solids
$\mathrm{q_i}$ is the tailings inflow in $\mathrm{m^3/s}$
$\mathrm{v_{95}}$ is the settling velocity in m/s of the 95 percentile.

However, where there is an ultrafine clay fraction, or where flocculants are used to achieve satisfactory water quality, the criteria may need to be based on quality of the return water and not on a minimum pond size. The deposition system therefore needs to be managed to ensure effective sedimentation of the finest portion and that minimum reservoir area is available at all times.

The surface slope of the hydraulically deposited beach relates to the characteristics of the waste and to the discharge velocity from each deposition point, and there are a number of methodologies for beach slope prediction (McPhail 2008). However, a rule of thumb for encouraging non-erosional sheet flow is to limit the velocity at each discharge point to between 0.5 and 1 m/s. This has been shown to limit erosion and channelling as the upper limit is less than the critical velocity required to move a particle of the equivalent diameter of approximately 200 μm (Leeder 1982). Ultimately, variations in plant performance and in climate may have a greater influence on the beach deposition and thus site-specific experience is the ultimate governing element. The Operating and Maintenance Manual prepared at the design stage for the pre-deposition works should include the disposal strategy to be adopted during the early stages of operation with the following key parameters as the driver:

- hydraulic placement to maximise available storage capacity by sub-aerial deposition;
- hydraulic placement to ensure ongoing stability of the confining embankment;
- placement strategy to encourage consolidation via the embankment and under-drainage;
- controlled deposition to manage the size and location of the supernatant pond;
- disposal management to minimise the potential for airborne pollutants;
- management of seepage control to maximise collection and recycling;
- management of disposal practices to minimise operating costs;
- instrument installation in order to confirm storage parameters;
- disposal management to facilitate early implementation of the closure strategy.

The deposited wastes should be regularly tested and fully instrumented to ensure that the disposal system performs in accordance with the design parameters at all stages of operation and closure. The Manual should set out the monitoring and instrumentation recording practices and the general inspection criteria and should be regularly updated to reflect site disposal and operating experience.

5.4.2.3 Basal Liners

The designer should recognise that consolidation of an extractive waste is adversely affected by the installation of a geomembrane liner throughout the MWF. This has the effect of reducing drainage, inhibiting consolidation and densification and reducing overall storage efficiency (Cambridge and Dale 1993). There are numerous sites where drainage has been inhibited in this manner, with the result that long-term increases in stored density were negligible and rehabilitation required the installation of band drains or their equivalent in order to achieve access to the surface of the depository at closure. The consolidation rate in a MWF is significantly reduced as the proportion of fines in the waste increases. The rate of consolidation is inversely proportional to the square of the length of the minimum drainage path and thus, in a laminated system with a potentially elevated k_h/k_v ratio, reducing lateral drainage can significantly impair consolidation rates and increase the required storage volumes. Consolidation rates in the deposited waste products are often enhanced by the installation of a drainage layer over the basal geomembrane, often supplemented by additional drains installed on the face of the embankment liner. However, the efficiency of such measures will depend on the establishment of effective flow paths to these drains, the portion of fines in the tailings and the long-term ability to effect seepage control under gravity through buried pipelines or by pumping from deep collection sumps. The long-term effectiveness of such an underdrain system must be assessed during the design phase as blinding of basal drains with increasing tailings depths may reduce their life to a few years, if not months. Further, buried pipelines through the confining wall or the installation of pump return lines over the embankment crest increase risks to the integrity of the structure. Where a geomembrane underliner is proposed, the design of the deposition system should ensure that the storage calculations are robust and take into account the reduced rate of consolidation and thus of densification of the tailings which will result. Any cost-savings in embankment zoning or permitting are likely to be negated by the additional storage requirements and increased closure costs.

5.5 Water Management

The design of a MWF needs to consider the geotechnical and hydrological parameters conventional for any dam, but also to incorporate the flexibility to provide continuous water supply to the plant and to meet the stringent environmental conditions often associated with mining projects (Cambridge 2010).

A MWF, unlike a conventional water reservoir, involves the retention of both settled solids and process water which may, if released, give rise to degradation of water courses and of the downstream catchment. Flood control measures for MWFs therefore require environmental controls during operation as well as safe design against extreme events. Such measures are complicated by the construction method commonly adopted for such confining structures and by the staged crest raising with successive, often annual, lifts over a period of many years to meet the demands of process and mine life. The facility will therefore need:

- to be capable of flood management at every stage of construction, and thus may require to incorporate a series of hydraulic control structures (emergency spillways) throughout its operational life;
- to provide a robust water supply, since the majority of the water used during mineral processing is likely to be derived from recycling of that discharged with the hydraulic fill into the depository;
- to comply with strict regulation of any discharge into local water courses, or indeed to accommodate zero release where there are overriding environmental concerns.

5.5.1 Water Balance

Under normal operating conditions the annual water balance for a MWF is used to address long-term storage requirements and to assess seasonal excess or deficit, and comprises the following elements (Fig. 5.13):

- process supply;
- other potential industrial demands;
- precipitation from both residual and upstream catchments;
- losses due to seepage;
- encapsulation in the settled solids;
- evaporative losses;
- inflow from mine or open pit dewatering.

The water balance will determine annual and monthly storage volumes whilst also defining flood capacity and any discharge requirements. The ability of an operator to manage the water balance effectively over the life of the project will be heavily influenced by the permitting conditions, i.e. the agreement as to the permitted quality and volume of any waters discharged into the downstream environment. On many mine sites the water quality of the reservoir and the sensitivity of the downstream receptors may preclude the release of waters at any time, and a "zero controlled-release" facility may be a condition of project development. Under such conditions the designer will need to ensure that the MWF, as the only significant water storage body on the mine site, has sufficient capacity to enable it to be operated in a compliant manner. For such facilities some mitigation can be achieved by the expedient of reducing runoff entering the MWF by diverting as much of the upstream catchment as is practicable, i.e. the effective separation of catchment and process waters (Fig. 5.13). A careful balance must be struck, however, between

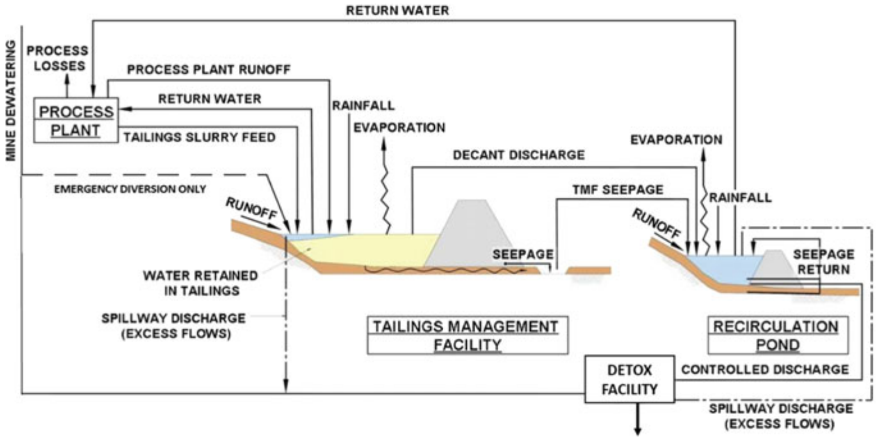


Fig. 5.13 MWF water balance

upstream diversion and continuance of water supply during dry periods, requiring detailed calculation of the monthly water balance for all climatic conditions. Where regular discharge from the MWF is permitted, both volume and quality will be fully regulated via discharge consent. Regardless of this consent, the operator must have the ability to control and manage water levels in the reservoir in accordance with the permit and with safe operation under all circumstances, whilst ensuring water supply for continued plant operation.

The development of a MWF water balance is influenced by the various project elements, including the tailings continuum, water availability, the environment and operational constraints as well as the recycle and re-use criteria of the process plant. Water used to transport the hydraulic fill to the MWF and released to the supernatant pond will be recovered for re-use in the process. In water-negative environments, additional make-up supplies will be required from external sources such as groundwater, mine or open pit dewatering and/or natural watercourses. Separate surface water impoundments are often developed to provide both a source of clean or raw water for use in key process elements such as gland seals and potable consumption and, additionally, as a robust industrial supply during periods of low rainfall and drought. As the primary water storage facility on a mine site the MWF may be required, either seasonally or throughout the year, to receive mine water from the open pit or from underground. However, it should be recognised that all additional water derived from external sources, particularly from the extraction operations, must not detract from the quality of the process feed abstracted from the MWF supernatant pond, and the water balance should allow for seasonal fluctuations in the inflow from such sources. The generic water balance presented in Fig. 5.13 illustrates the importance of this issue for an extractive site.

The water balance must not be considered in isolation but must be fully integrated with the parameters for the MWF which, generally being the largest water retaining body on the site, will play a major role in site water management. The control of water levels, and in particular the maintenance of an appropriate freeboard (Fig. 5.14) between the surface of the supernatant pond, minimum beach and embankment crest levels at all times, is an important design and management factor.

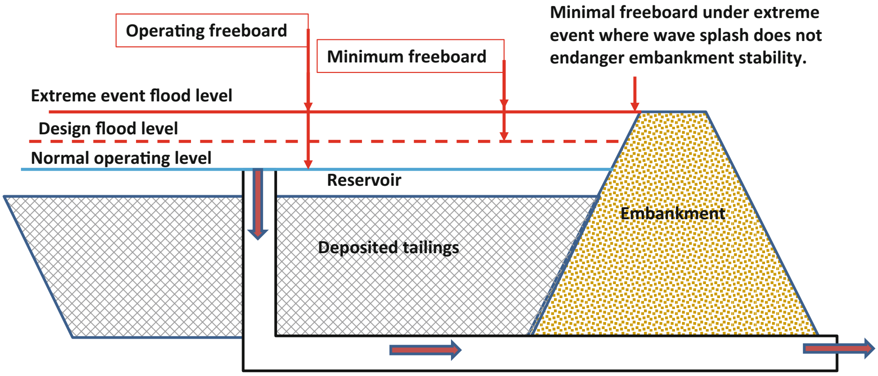


Fig. 5.14 Critical freeboard considerations for a MWF (Cambridge 2015)

5.5.2 Flood Studies

The hydrology of the catchment to the MWF must be assessed using the most appropriate national rainfall and runoff models and the approach to this assessment should be similar in character to that adopted for water supply reservoirs. The flood model should consider both summer and winter storm events and adopt appropriate catchment characteristics in order to derive a range of flood hydrographs for adoption in accordance with national and international practice. The design criteria adopted should include the ability to retain or, where permitted, to pass in safety the extreme hydrological event during operation. In addition, where an embankment is stage-constructed, the facility should be designed to retain similar flood volumes at all times by virtue of the storage capacity of the reservoir and the operating freeboard. The robustness of this freeboard should be tested as part of the risk assessment with respect to the potential for extreme events, such as landslide of the upstream valley slopes into the MWF and failure of the diversion dam towards the main depository.

During the final construction stage a long-term spillway structure may be required in order to cater for the post-operative condition and to meet the requirements of long-term flood management.

The facility should be designed to accommodate both extreme drought and flood conditions. The mine site water balance will be used to derive storage requirements and to assess the volumes of any necessary releases. Of particular importance is the flood standard to be applied to the storage facility, which must accord with current national guidance for dams for the identified risk category, as well as with accepted international practice. These flood standards are as follows:

- The "extreme design flood" for a MWF is generally defined as the Probable Maximum Flood (PMF) and corresponds to the "safety check flood" for a water supply reservoir. It is considered acceptable practice for the crest, waterways and energy dissipater to be on the verge of failure but to exhibit marginally safe performance characteristics under this extreme flood condition.
- The "normal design flood" for a MWF is the equivalent of the "design flood" for a water supply reservoir and represents the inflow which must be discharged under normal conditions with a safety margin provided by the freeboard. It is usually taken as a percentage of PMF, or a flood with a given probability of exceedance, such as 1:100-years or 1:1000-years. However, for a MWF this standard is only applicable if an emergency spillway is maintained at all times and where discharge of an extreme event (such as >1000-years) is permitted (Sect. 5.5.3).

It is not considered appropriate to adopt return periods with an enhanced probability of occurrence for the normal design flood unless the predicted outcomes arising from overtopping of the MWF during a more extreme event can be shown to have negligible consequences for life and the environment. The likelihood of such a scenario being acceptable in Europe is considered to be extremely unlikely and thus the internationally accepted return periods for the extreme event of 10,000-years or the PMF should be adopted for all stages of a MWF from the initial deposition period through to closure.

Therefore, in summary, the flood study and risk analyses depend on the following:

(i) selection of appropriate rainfall and runoff parameters;
(ii) identification of potential downstream impacts;
(iii) identification of preliminary flood risk category for a MWF based on potential impacts;
(iv) identification of all potential reservoir conditions (under all operating scenarios);
(v) identification of all potential overtopping mechanisms;
(vi) review of flood risk data with subsequent validation of the proposed routing analyses;
(vii) establishment of a critical flood verification system;
(viii) review of flood routing results for consistency;
(ix) future-proofing of records of analyses.

5.5.3 *Flood Risk*

The MWF must be robust under the appropriate flood standard and thus for a "zero controlled-release" facility sufficient freeboard will need to be available at all times to store this event (generally the PMF or equivalent).

As discussed above (Sect. 5.5.2), for most MWFs the flood design criterion will always be the PMF. However, it is evident that this imposes a significant restraint on the design of the facility and, moreover, may impose overly conservative operating criteria and negatively impact on disposal efficiency. Maintaining such retention capacity at all times often results in inefficient construction and operation, and may threaten the viability of the facility and thus of the project. In the past ten-to-twenty years, as the magnitude of design floods has tended to increase and discharge controls have become tighter, a more flexible approach to the design and operation of emergency spillways has been developed with regulators in Europe. It has been recognised that a limited discharge from a MWF during an extreme flood event will be likely to have a negligible contributory effect on any flooding impacts downstream. Further, the environmental risks are also likely to be minimal due to the significant dilution which will occur during such events.

In recent years, therefore, flood control structures for MWFs in Europe have been designed to minimise reservoir rise resulting from a combination of process water discharges and extreme flood events. For safety reasons these structures are required to be robust under the extreme design flood. However, the design no longer considers only retention of the PMF but addresses the discharge of a portion of this volume via an emergency spillway. This pragmatic approach assumes a two-tier flood control system, with the safety design being based on robustness under the PMF and the operating design on environmental constraints and permitting requirements (Cambridge 2010). In the UK the operating criteria at three facilities have been modified during the last twenty years and, though emergency spillways are provided to pass the PMF in safety, the approach to the normal operating conditions has been revised and a more realistic, less onerous but environmentally acceptable set of flood release standards derived. Accordingly, the hydrology of the catchment contributing to flood design for the MWF has been assessed to define not only the PMF but also the 1000-year event, from which peak flood discharges and volumes have been calculated. Flood routing of the extreme event through the emergency spillway has been undertaken to confirm the capacity of the waterways and, in addition, the flood volume for the lower-bound (1000-year) event has been assessed. These reservoirs are now operated on the basis that all floods up to the 1000-year event will be retained and that sufficient freeboard is maintained to accommodate this flood volume at all times (Fig. 5.14) (Cambridge 2015).

The overall design approach for a MWF should be to provide sufficient storage and to adequately manage water during operations such that no process water is released directly from the hydraulic fill containment into the environment other than through internal seepage during the life of the facility. It is conventional for storage facilities to be designed, constructed and operated in accordance with good international practice and that the same risk categories as are used for large raised reservoirs be applied to flood criteria (Cambridge 2008a, b). Therefore a mine waste facility which includes the potential to store a significant volume of water [often cited as being more than 10,000 m^3 (HMSO 1999) would be placed in the highest risk category for flood storage (ICE 2015a, b) due to the implications of an untoward release for both life and the environment in the downstream catchment. A suitably qualified civil engineer should therefore be engaged to advise on the necessary flood standards to be applied in order to ensure that the required hydrological assessment is compliant with this standard. A “suitably qualified civil engineer” in this instance is one with sound hydrological experience who is competent both to define flood standards and to approve the hydrological model to be used.

In summary, therefore:

(i) the flood standard to be applied to the MWF should be in accordance with current national guidance for dams for the identified risk category but should generally be the PMF;
(ii) a MWF should include robust storage capacity or an emergency spillway designed to pass in safety the PMF at all construction stages, as overtopping of the confining embankment is rarely, if ever, permissible;
(iii) the engineering and cost implications involved in retaining the PMF may require an alternative flood management approach;
(iv) in some jurisdictions it is accepted practice for a MWF to be designed to retain all floods arising from storm events up to and including the

1:1000-year event without spilling but to pass in safety those arising from greater storms up to and including the PMF;

(v) the acceptance of the design criteria must be based on a suitable risk assessment to confirm that flood discharges do not compromise environmental risk downstream;

(vi) if the project is to be independently reviewed and approved, the brief for the flood study should be agreed with the review engineer in advance.

5.5.4 Emergency Spillway

A major design criterion for a MWF is that it can either store or pass in safety the flood arising from the PMF on the site. As previously indicated, it is often uneconomic to store the PMF, and thus the extreme event must be discharged into the downstream catchment in a controlled manner via an emergency spillway. This operating criterion is obviously dependent on any additional downstream flood risk or environmental detriment being assessed as not significant and posing no additional threat to life or the environment. Under these circumstances the MWF needs to include a suitable hydraulic control structure and outlet channel for the extreme event. The design criterion should be the full containment and control of the routed peak flow to a point beyond the toe of the confining wall at which out-of-channel flow poses minimal risk to the embankment. The control structure is normally achieved with a series of weirs, either in concrete or in natural rock, which are constructed sequentially up the abutment to suit the embankment phase. Often, for reasons of economy, each successive spillway discharges into a single outlet channel which is also extended at each stage but which is located outside the final footprint of the MWF.

The precise design of such structures is site-specific and is dependent on catchment size, topography, rate of rise and land ownership. However, it is now accepted that all MWFs must be robust under the extreme event and that the risk to the embankment of either overtopping or toe erosion should be fully mitigated in the design.

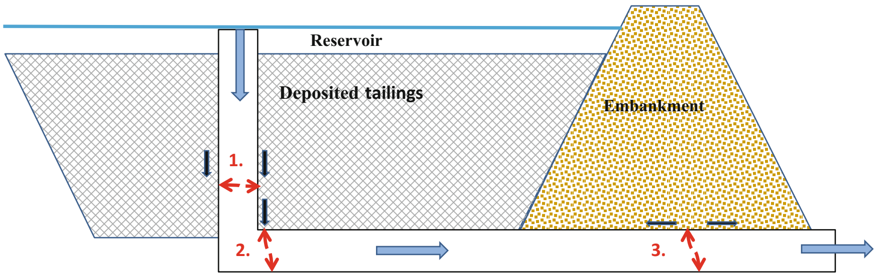
5.5.5 Decant Design

The decant structure functions primarily as the return system for recycling stored water to the plant throughout operations. The decant facility needs to be designed in tandem with the flood management system and, in some MWFs, may also function as the emergency spillway where the catchment is limited and outflow can be guaranteed. The decant may comprise either a gravity system with weirboard control or a pumped return from a floating barge or fixed tower. The engineering design may therefore comprise a barge and floating walkway or causeway or, alternatively, a buried concrete structure fitted with a rising offtake crest. The decant may also need to function as the emergency drawdown facility.

For each system the key design requirement is functionality under all operating scenarios, including the full range of climatic conditions. Therefore even a simple floating barge and pipeline or walkway must be able to operate in all circumstances and provision must be included for access for operational and emergency reasons during extreme weather, i.e. under heavy rain, snow, ice or strong winds, and the control valves located such that flow can be initiated or shut down in safety under all conditions, often defined as during a severe storm in the middle of the night.

Surface or fixed decants vary in design from central towers to side chutes, are generally constructed in concrete and include a system for raising the offtake level as the height of deposition increases. Circular towers located in the centre of the depository have the advantage of enabling peripheral deposition of hydraulic fill and of reducing the risk from flood events, and can be the most efficient and cost-effective means of returning water since the associated infrastructure is fixed and installed during pre-deposition. However, central towers carry an increased risk due to the structural issues associated with their configuration, particularly from the vertical loading imposed by the consolidating tailings, from the vulnerability of the tower foundations and from the presence of a buried pipeline through the embankment (Figs. 5.15, 5.16, 5.17 and 5.18). The risks were evidenced by a number of tower decant incidents which occurred in the 1960s and 1970s. These structures failed structurally at or about 20 m in height due to the stresses imposed by the consolidating tailings (Forbes et al. 1991).

The realisation of the implications of such high stresses has led to modified designs which address the effects of tailings consolidation and the risks associated with buried pipelines and appurtenant structures. The decant design must therefore seek to mitigate all risks arising from the configuration and operation, and address the following:



Critical stress locations:

1. **Vertical section of decant crushed due to loading imparted by consolidating tailings.**
2. **Horizontal portion fails in shear due to vertical thrust imposed by vertical section.**
3. **Horizontal pipeline fails in tension due to spreading of embankment foundations.**

Fig. 5.15 Critical structural considerations for the buried section of a vertical decant tower (Cambridge 2015)

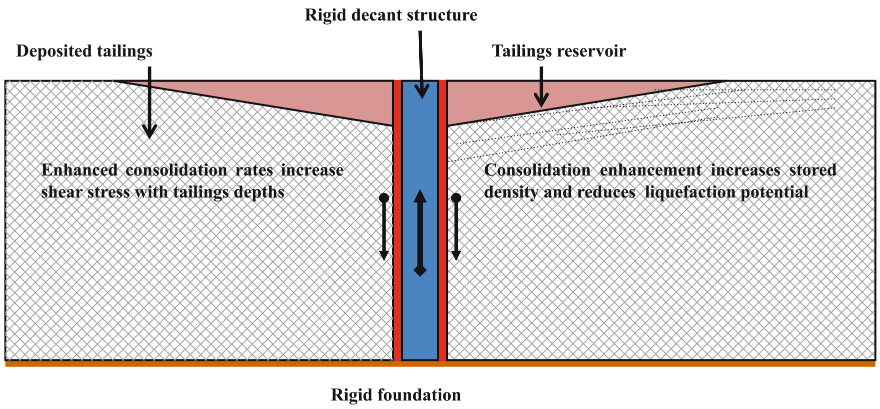


Fig. 5.16 Critical structural considerations for a vertical decant tower (Cambridge 2015)

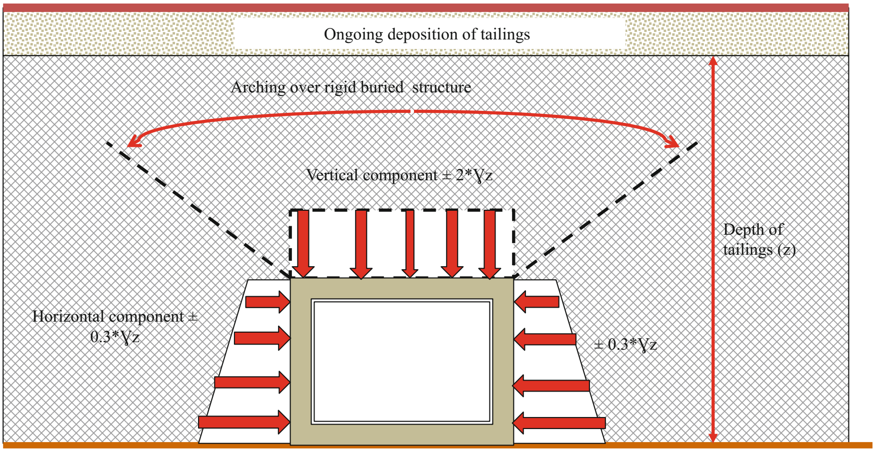


Fig. 5.17 Critical stress concentrations on a buried culvert (Cambridge 2015)

(i) adequate hydraulic capacity to meet all process flows and flood criteria;
(ii) robust construction to meet both short- and long-term loadings;
(iii) ease of access and operation, enabling the accommodation of successive raises;
(iv) full function under all emergency conditions;
(v) the design to mitigate any adverse structural or functional effects arising from adverse water quality or geochemistry of the hydraulic fill;
(vi) the particular requirements of inspection and monitoring.

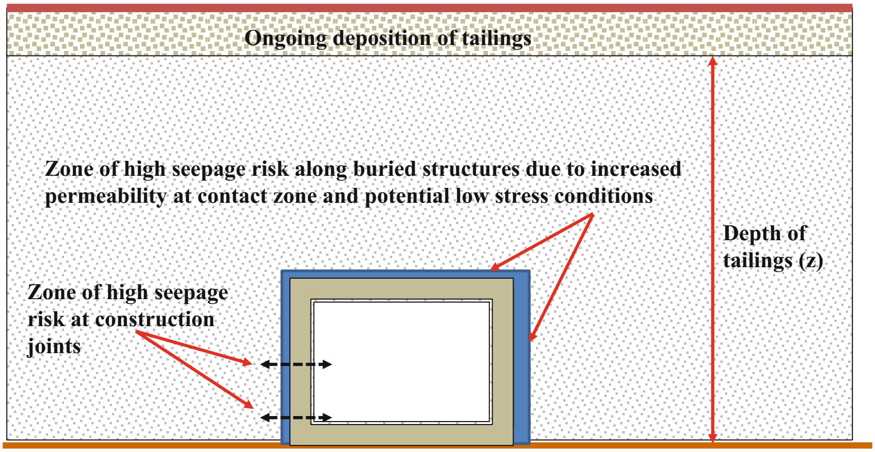


Fig. 5.18 Zones of potential high/preferential seepage (Cambridge 2015)

5.6 Emergency Planning

5.6.1 *Background*

The EWD requires that emergency planning be an essential design element for all Category A mine waste facilities. Categorisation therefore requires assessment of the hazardous nature of the hydraulic fill and of the risk posed by the storage of this waste, and is a two-stage process (Fig. 5.19). The characterisation process for

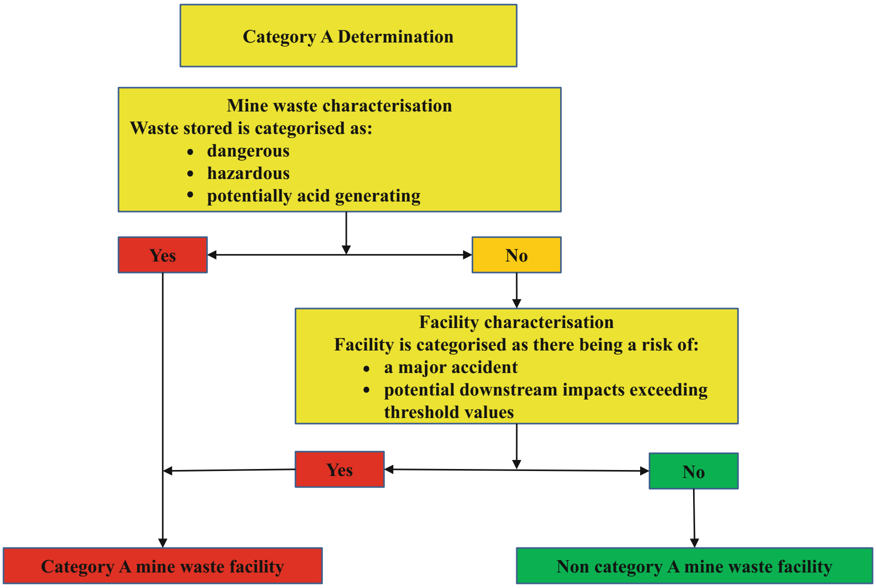


Fig. 5.19 Facility characterisation for emergency planning

determining whether a mine waste facility is to be classified as either Category A or Non Category A is based on the following:

- whether the contained material is hazardous/non-hazardous or dangerous/non-dangerous;
- whether the potential downstream impacts arising from a failure exceed the threshold values of depth and velocity of flow after a breach has occurred.

Regardless, therefore, of whether the mine waste characterisation determines the MWF as Non Category A, the facility may, by virtue of potential downstream impacts exceeding the specified threshold values, still be classified as Category A. Emergency planning is therefore required for the majority of MWFs in Europe in order to assess the downstream impacts arising from a failure, to determine the extent and severity of any social and environmental effects and to develop both mitigating measures and the off-site action plan.

Emergency planning requires the testing of the design and construction system to assess the most likely (credible) failure mode for the MWF. The adopted most likely credible mode needs to be developed rationally and the failure modelled in order to provide an indication of the downstream risks, if any, and the magnitude of the hazard posed by the facility. Though the development of the critical failure mode and the subsequent modelling may be undertaken by sophisticated computational methods, this can be an expensive process and in many cases may not be cost-effective, noting that the model is only required to provide an order of magnitude assessment of the downstream impacts rather than precise numbers of people and properties at risk. On the basis of the principle of design risk (Fig. 5.20) an alternative methodology using a more pragmatic approach to failure can be adopted

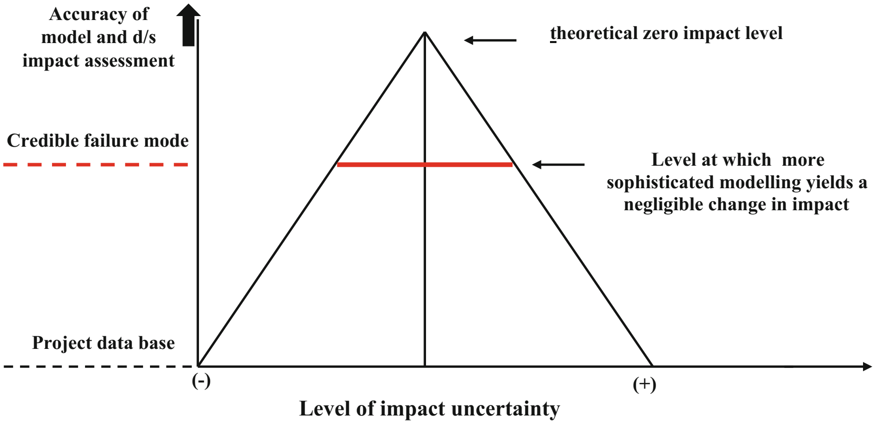


Fig. 5.20 Defining inundation model parameters based on relative impact downstream (Cambridge 2013)

in many instances and may prove adequate in establishing the extent of any downstream impacts and for emergency planning. This methodology is briefly described below in the knowledge that national guidelines may determine the approach to emergency planning.

5.6.2 Development of a MWF Failure Model

The design process for a mine waste facility should involve the identification of all potential hazards, not only during operation but post closure as well, as previously described. The key risks to be addressed should include a full evaluation of both short- and long-term risks to life and to the environment downstream and the final design stage include a detailed risk assessment of the stability of the confining embankment under all anticipated conditions. Therefore, for a correctly designed and operated facility, the initiation of failure leading to a breach is considered to be extremely unlikely since:

- the confining embankment should have a design factor of safety under both normal operating and extreme conditions which exceeds the minimum recommendations published in national and international guidelines;
- the embankment construction programme should ensure a crest height significantly in advance of both tailings and reservoir impoundment, thus ensuring that freeboard levels exceed minimum flood requirements at all times and that there is a very low probability of overtopping during an extreme event;
- the inspection and monitoring of the facility, the instrumentation and the embankment performance data should ensure that any untoward issues are rapidly identified and suitable mitigating measures adopted;
- annual, at minimum, independent inspection should confirm ongoing stability and correct operation and management of the facility, and identify any measures required in the interests of safety which need to be addressed in order to prevent the occurrence of future untoward incidents.

The failure of properly designed and operated mine waste facilities is recognised as having low-probability but high and serious consequence. It is mandatory within the EU for all Category A facilities to be assessed in order to determine the hazard potential which would arise should the embankment fail in such a manner that a breach were to develop and lead to an uncontrolled outflow of the contained liquid and solids. The purpose of failure modelling is to establish the worst credible event which could lead to the development of a dam breach, and to determine the extent of any subsequent downstream inundation and risk to life and the environment using the source-pathway-receptor approach. Such an assessment enables emergency planning by the operator and requires, at minimum, the identification of the following (Cambridge et al. 2014):

(i) Tier 1 assessment—to identify all potential and credible failure models and to establish the critical mode;
(ii) source—determination of the volume of solids and liquids disturbed and potentially released during the critical failure;
(iii) pathway—determination of the release mechanism for the material from the designed position towards a potential receptor;
(iv) Tier 2 assessment—establishment of the probability rankings for the credible failure modes and the identification of the critical mode to be modelled for emergency planning;
(v) receptor—assessment of the extent of inundation of the downstream catchment and of any centres of population or river and estuarine systems.

Establishing the credible failure modes may follow accepted national methodologies, which are generally based on failures of water supply reservoirs confined by embankment dams for which the critical condition is often assumed to be overtopping. The critical failure model for such reservoirs assumes a full-depth breach developing to near foundation level, with the basin emptying rapidly in a Teton-type failure (Snorteland 2013) and there are well-documented hydrodynamic models available for establishing the resulting inundation extent. For these reservoirs the rate of release is dictated by hydrodynamics and therefore no Tier 1 assessment is necessary (Fig. 5.21).

However, a failure in a MWF containing both water and settled fine particulate materials may, dependent on the characteristics of the depository, result in a partial breach through the dam wall and the rapid evacuation of the fluid portion and of only the more mobile fraction of the mine waste. The result is a Kolontar-type failure (Javor 2011) with the release dictated by both geotechnical and hydrodynamic characteristics (Fig. 5.22).

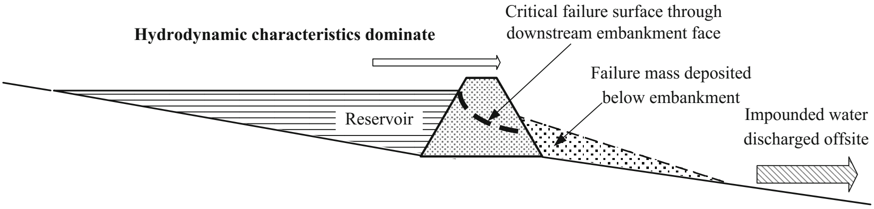


Fig. 5.21 Single-phase hydrodynamic model for a water supply reservoir

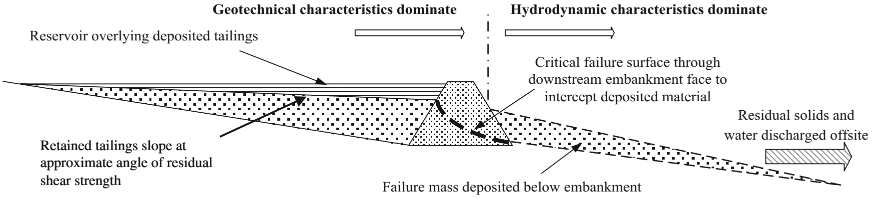


Fig. 5.22 Two-phase model for a stage constructed MWF

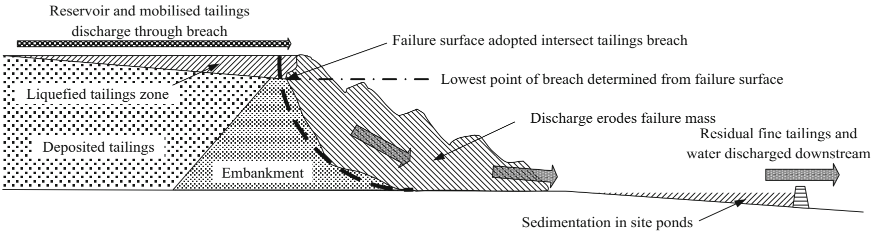


Fig. 5.23 Critical failure mode for a MWF

The initial Tier 1 risk assessment to determine the worst-case critical breach scenario for such a MWF should reference previous dam failure studies (ICOLD 2011) since a review of historical failures indicates that two-phase breach models are appropriate as a means of both determining the failure mode and predicting the event outcome (Cambridge et al. 2014). The model is predicated on the volume of free water stored on the facility at failure and separates the event into upstream and downstream phases. The failure characteristics, as outlined in Fig. 5.23, are determined as being geotechnical upstream of the embankment toe of the initiating failure surface and hydrodynamic downstream. A two-phase model enables a realistic assessment of the volumes of both solid and liquid waste involved in the failure, and the development of the breach mode permits conventional hydraulic models, such as those adopted for water supply reservoirs, to be used for preparing downstream catchment inundation maps and for determining sediment deposition.

Though the failure of a correctly designed and constructed MWF is considered unlikely, it is necessary to assess which modes should be addressed in developing a critical state for use in a breach analysis. Paradoxically, failure of a stable confining dam has to be considered in order to allow an emergency off-site plan to be prepared and the potential downstream impacts to be identified. The necessary engineering studies, requiring the use of basic risk assessment methods in order to identify and model the most likely failure mode and outcome, are summarised in Table 5.11.

5.6.2.1 Geotechnical Phase

Though the design should incorporate measures which, if implemented, would mitigate against failure of the facility at all stages, the identification of critical failure modes should be based on the least well-defined parameters. The critical states which, under realistic worst-case conditions, might precipitate a failure of the MWF should therefore consider, in particular, the following:

- local geological unknowns;
- inadequate construction and material control;
- poor operation and management of the facility.

This combination of parameters, no matter how unlikely where strict statutory controls on both design and construction are imposed, must be considered in the

Table 5.11 Staged approach to basic MWF breach modelling (Cambridge 2013)

Stage	Geotechnical phase	Basis
1	Critical failure modes	Identification of all potential hazards Identification of initiating event
2	Critical failure model	Identification of most-credible failure models Definition of critical location Definition of critical climatic effect (sunny- or rainy-day failure)
3	Critical failure mechanism	Development of failure progression Identification of breach extent Definition of solid and liquid volumes implicated in critical failure
Stage	Hydrodynamic phase	Basis
4	Discharge hydrograph	Development of breach hydrograph [Froelich equation, (Froelich 1995)]
5	Inundation modelling	Development of inundation mapping using standard hydrological models Preparation of inundation maps (in terms of extent, depth and velocity of flow) Assessment of attenuating elements in downstream catchment Definition of sedimentation of solid fraction within catchment based on flood velocities Definition of residual volumes carried downstream
6	Final assessment	Review of inundation extent against location of at-risk properties Review of depth and velocity profiles at at-risk properties using EWD criteria Determination of Category A/Non Category A status on the basis of breach model Preparation of input to both on- and off-site emergency plans

Tier 1 assessment in order to identify the range of credible failure modes which are considered most likely to result in embankment or structural instability (Table 5.12). Review of these modes should enable definition of the critical locations for the development of the breach, of the anticipated configuration of the failure surface and therefore of the volume of embankment fill involved. The definition of the failure surface will enable the breach height to be determined and this will lead to an assessment of the volume of the contained fine mine waste likely to liquefy, flow and be released. This volume can conservatively be based on a conical surface defined by the residual shear strength of the hydraulic fill.

Table 5.12 Example of critical failure mode assessment (Cambridge 2013)

Initiating event	Typical mitigation in design	Credible/non-credible	Failure mode
Waterway design		Cr/NCr	FM01-N
Overtopping	Spillway designed to pass PMF	NCr	
Spillway blockage	Robust storage volume with no catchment debris	NCr	
Erosion of spillway	Construction quality control	Cr	
Decant failure	Floating pump station	NCr	
Embankment design			
Seismicity	Rockfill dam stable under dynamic loading	NCr	
Uncontrolled seepage and piping	Factors of safety on filters >10 Construction quality control	Cr	
Erosion of underdrains	Factors of safety on design >10	Cr	
Untoward settlement	Construction quality control	Cr	
Foundation competence	Underlying geology and construction quality control	Cr	
Abutment competence	Underlying geology and construction quality control	Cr	
Old mine workings	Foundation preparation and structural mitigation measures	NCr	

5.6.2.2 Hydrodynamic Phase

The development of the breach configuration enables the release discharge hydrograph to be established and incorporated into a standard (national) flood attenuation model from which the peak discharge velocities and flow depths throughout the downstream catchment can be determined. These data enable an assessment of impact against the critical threshold values included in the EWD, which are defined as follows:

- depth of water or slurry exceeding 0.7 m above ground;
- velocities of water or slurry exceeding 0.5 m/s.

For a MWF, the velocity mapping also enables an assessment of the proportion of the hydraulic fill and the fine eroded debris which will settle-out in the catchment as a result of sedimentation. The peak flows throughout the inundation area can be used to assess the minimum settling velocity and the equivalent particle size (Leeder 1982). On this basis the material to be retained in the upstream catchment can be defined and a realistic calculation made of the tonnage of solids eventually released into the downstream catchment. Using this method it may be proved that only the finest particle sizes will be released through the breach into the downstream catchment. The proportion of this material should represent a reasonable upper-bound estimate of the total volume likely to be involved in the event. It should be recognised that, due to the shape of the outflow hydrograph, the peak velocity is transient and therefore the solid fraction released may be considered to be extremely conservative.

The results of the inundation mapping can be used to determine the areas of flooding and the velocity and maximum depths at each part of the catchment assessed. The locations at which high velocity flows will be confined to the existing channel should be evaluated, together with a broad indication of the areas where properties might be at risk. The extent to which out-of-channel flow occurs and exceeds the EWD thresholds for risk to life and property must be identified. The main area of environmental impact arising as a result of the deposition of the silt can also be identified, noting that evidence from the review of historic failures indicates that the maximum impact may involve the settlement of only a thin (less than 25 mm) veneer of silt and fine tailings over the flood plain or inundation area, with the major depth being restricted to close proximity to the facility.

5.6.3 Emergency Planning

The EWD requires the following to be completed for each Category A MWF:

- identification of the major accident hazards;
- preparation of a major accident prevention policy;
- preparation and implementation of an internal (on-site) emergency plan;
- preparation of an external (off-site) emergency plan.

The operator is therefore required to identify the major accident hazards and to incorporate the features necessary "to prevent such accidents and to limit their consequences for human health and the environment" into the design, construction and operation. As part of the design, therefore, a major accident prevention policy must be prepared and an on-site emergency plan developed. This plan should be based on the following:

- the development of a realistic failure scenario;
- the assessment of the volumes of solids and liquids which would potentially be released during a breach;
- the assessment of the risk to life and properties;
- the assessment of the downstream environmental impacts arising as a result of deposition of any silt carried downstream with the discharge.

These data should enable the operator to develop the on-site emergency plan, specifying the actions to be taken on-site in the event of an accident. The Competent Authority is required to generate the off-site emergency plan, which specifies the actions to be taken off-site in the event of a major accident. This plan should be based on the information supplied in the emergency on-site plan, which must provide all information required to minimise the consequences of a major accident for human health and to assess and minimise the extent, actual or potential, of any environmental damage. The format for such plans is generally specified in national regulations and guidelines, which should be referenced for content and detail.

5.7 Closure and Rehabilitation

5.7.1 Closure Philosophy

The design of a MWF is determined by its primary function, namely to store the extractive waste in a safe and stable manner. The design process should involve an assessment of environmental and social impact considerations and include both controls and mitigation measures in order to meet regulatory and environmental permitting requirements. This should include closure as an integral part of the design from inception onward ("design for closure") and entail not only closing and rehabilitating the facility but ensuring, to the extent practicable, its long-term re-integration into the biological, cultural and physical landscape. This good practice approach formulates the ultimate closure objectives into an integral part of a design rather than a closure plan being developed at a later stage when the operation of the facility is advanced and which, by necessity, is required to mitigate the impacts and risks resulting from the original design and operation. The closure process and restoration is therefore a major parameter in the design and becomes an integral part of the operational mode. Designing for closure requires a clear set of post-closure objectives for the facility, based on landform and after-use, the environmental setting (landscape and land-use) and long-term stability. Engineered closure involves capping, surface rehabilitation and the development of the final land use, together with the production of the engineering fills and soil-forming materials needed to support this. In addition, the development of the final closure system involves the assessment and mitigation of all short- and long-term geotechnical, geochemical and hydrological risks.

The key elements of the closure plan will therefore comprise the following:

- management and secure placement or treatment of any high-risk materials, such as ARD-inducing wastes, during operations;
- development of an engineered closure cover to mitigate all geotechnical and geochemical risks;
- minimisation, where practicable, of water storage on the surface of the MWF;
- ensuring suitable site drainage, flood control and water management;
- development of seepage management and control, including the provision for passive or active water treatments for ultimate discharge;

- development of appropriate land-use objectives, including covers, suitable vegetation types and their management and the potential benefits or risks associated with incorporating woodland or deep-rooted shrub species as part of the long-term objective;
- establishment of a clear strategy for future ownership and after-use, including the important functions of site management and transfer of responsibility from the operational company;
- establishment of appropriate financial provisions (as required under the EWD) and of potential income streams.

It is also critical to note that a closure plan is normally required for submission as part of an Environmental and Social Impact Assessment (ESIA) report. As such, the closure plan will be subject to the consultation process required under ESIA procedures and the key elements set out above be subject to both an internal and external consultation process involving a range of stakeholders.

5.7.2 Design for Closure

At the end of the operational life the MWF may comprise a large embankment dam containing some millions of cubic metres of deposited hydraulic fill and a residual industrial water reservoir, together with the saddle dams, pollution control dams, hydraulic structures and associated infrastructure. Such facilities need to be designed and engineered for closure from the outset such that at the initiation of the closure process and decommissioning phase there is a planned transition from operational to post-closure conditions. Further, the extent of additional re-engineering works needs to be minimised so that there is no requirement to compromise on after-use and landscape options. Preparation of a closure plan at the design stage is a strict requirement under both the EWD and EU ESIA Regulations, and there is the added requirement for regular review and updating of both the plan and the supporting engineering and closure strategy. Information and guidance on closure planning, options and procedures is provided in the BREF and in ICOLD bulletins (BREF 2009; ICOLD 2011; ESIA Regulations 2014).

The process of closure planning and implementation both prior to, and during, operations will typically involve:

- preparation of the closure plan and of the decommissioning strategy at permitting stage;
- regular review of the closure plan throughout the operating life, involving external consultation with a range of stakeholders as required by the permit;
- testwork to predict the geotechnical and geochemical behaviour of the confining embankment and its constituent materials, as well as of the hydraulic fill, in order to enable the design to take account of long-term degradation, ARD, residual contamination and erosion potential;

- testwork to assess the suitability of soil-forming materials, as well as to predict their geotechnical and geochemical behaviour;
- initiation of trials to investigate, test and demonstrate rehabilitation solutions both for cover materials and for vegetation;
- progressive rehabilitation of the containment structures and of the disposal areas;
- initiation of engineering works to achieve the final landform prior to cessation of extraction operations on the site.

In summary, the decommissioning and closure objectives should be as follows:

(i) pre-decommissioning—modification of the deposition system to achieve the final landform and, in particular, to minimise, to the extent practicable, potential surface water storage;
(ii) post closure, short-term—immediate stabilisation of all surfaces in order to manage extreme flood events, reduce the potential for wind- and water-erosion, to control infiltration and seepage and to develop the final landscape and after-use;
(iii) post closure, long-term—maintenance of ongoing geotechnical and geochemical stability and the development of an appropriate sustainable after-use requiring minimal intervention.

Designing for closure from project initiation, together with the early identification of a suitable and manageable after-use, will help to ensure that the long-term objectives can be met and will minimise the closure costs and reduce the long-term liabilities. The development of a closure strategy which is regularly updated during the operating life of the facility enables the deposition system to be modified in the period immediately preceding closure. This should permit the final landform to be created to meet the closure objectives and may, by manipulating the plant, enable the initial, or in some cases the final, cover system to be placed hydraulically (CLOTADAM 2003).

Closure planning also requires both the instrumentation of the facility and ongoing testwork in order to obtain the following:

- geotechnical data in order to confirm overall stability at closure and the extent of any necessary buttressing or re-profiling works;
- piezometric and seepage records for the confining embankment and the deposited hydraulic fill in order to confirm the stability of the tailings surface in advance of the implementation of the closure plan;
- geochemical data for all engineered and deposited materials in order to confirm their long-term stability and their resistance to degradation and to enable the design and incorporation of any necessary mitigation or treatment works.

It is essential that the closure plan specify a sustainable after-use which is appropriate for the site location and includes provision for beneficial uses both in terms of livelihoods and the ecosystem. The proposed after-use and land management plan will be subject to external consultation under ESIA Regulations, and need to be compliant with the project permitting requirements. After-uses can range from those with direct economic benefits, such as agriculture, to less tangible but equally valuable services such as biodiversity. A facility comprising the long-term confining system for the storage of the hydraulic fill should be permanent, and be designed to be safe and stable at closure and, effectively, in perpetuity. The design must therefore take account not only of the immediate operational and safety needs, but satisfy the longer-term requirements for:

- integration into the landscape and land-use pattern, with an enduring beneficial use;
- reduction of ongoing liability and of potential for untoward releases in the future;
- anticipation of changes and circumstances over a long time-scale and under a variety of external and internal forces, not all of which will be predictable.

The location and design of a facility must therefore anticipate and incorporate five key long-term factors, together with the necessary considerations and requirements as shown below:

(i) Engineering containment of the hydraulic fill

  - geotechnical changes such as physical weathering and alteration of fills, as well as the degradation of liners and geomembranes or geofabrics, which may affect the stability of the retaining structures and the integrity of the containment;
  - hydrological changes such as degradation of embankment drainage materials and filter zones, cessation of operation of underdrainage and seepage control systems, as well as the functioning of the surface water management systems;
  - geochemical changes in the hydraulic fill, particularly the development of acid rock drainage, the leaching of toxic elements and the chemical weathering of the engineered materials;
  - extreme events, both seismological and hydrological, including provision for passing flood events around or through the facility.

(ii) Capping, covering and soil-forming materials

  - in many cases the hydraulic fill will be benign and will comprise a good soil-forming material without the need for additional growth media;
  - where the fill material is expected to be physically or geochemically active, or contains leachable contaminants, a capping layer or barrier may be required to isolate it from the overlying cover and vegetation system. Such barriers may take the form of low-permeability materials comprising geological or synthetic covers, or high-permeability capillary breaks. Regardless of the cover system adopted it will need to be robust against long-term disruption or deterioration and to include drainage provisions for control, diversion and management of incident rainfall and runoff and the reduction of seepage and infiltration;

- the soil-forming materials (SFM) such as overburden, screened waste rock with appropriate particle size distribution and other waste materials to be used for final restoration cover and amelioration should be identified and stockpiled during operations. Topsoil is rarely available in sufficient quantities and is not always appropriate for the required land use.

(iii) Land cover and vegetation

- all sites will ultimately be required to support a suitable land cover, comprising a functioning soil-plant system, for both visual and after-use reasons;
- vegetation is an important part of the long-term integrity of the facility due to:
  - beneficial effects of run-off modification, surface protection, erosion control and, in some circumstances, soil reinforcement with roots and buttressing of slopes;
  - negative effects, including increasing water infiltration, surface loading (trees) and rotational forces which can compromise structural integrity;
  - associated biota such as grazing or burrowing animals which, though potentially beneficial in discouraging tree development, may lead to increased erosion and to void creation.
- vegetation is dynamic, is subject to natural successional and ecological changes over time, and is influenced by the degree of management. In temperate climates the successional change is typically from ruderal herbaceous and grass vegetation through increasing scrub and woody vegetation to woodland. The development of deep-rooted shrubs and trees on the cover system may have long-term detrimental effects, including root penetration of liners and capillary breaks, thus reducing their effectiveness. This may lead to untoward deterioration of the after-use plans and necessitate the provision of long-term vegetation control systems.

(iv) Landform

- visual and landscape considerations are equally important aspects of the long-term after-use and function of the facility. Engineered, angular or regular slope profiles may require modification in order to create a suitable landform but must be designed such that the function of the confining system is not impaired and leads to reduced stability;
- the final landform, including slopes, perimeter and surface drainage, soil type and exposure, is also critical to the ability of the closure system to achieve and support a beneficial after-use.

(v) Responsibility and long-term management

  - establishment of a maintenance, monitoring and management programme for the facility after closure is required, including allowance for the necessary independent inspections and reporting together with ensuring both ongoing financial provision and defined responsibility. This can best be achieved by linking it to a beneficial after-use and economic activity, whereby management is not a burden but is a normal part of the land use and livelihood pattern.

The design of the MWF should include a strategy for operation and management during the immediate pre-decommissioning period towards the end of the life of the facility, which will typically include:

- anticipation of the proposed closure landform by developing the disposal of the hydraulic fill during the final years of operation to minimise post-closure engineering works on the surface of the MWF;
- decommissioning of the hydraulic filling reticulation system and other infrastructure, including staged removal of pipelines, pumps and other structures, noting that the decant and/or emergency spillway may need to be retained, together with seepage control systems and provision for water treatment;
- engineering changes to the landform and to both surface and internal drainage, though these must not compromise the long-term geotechnical stability or the hydraulic fill containment system;
- stabilisation of the surface of the hydraulic fill to enable the safe installation of the proposed capping system, soil cover and the post-closure rehabilitation and aftercare;
- long-term maintenance and management to ensure that the depository remains stable and that the revegetation and after-use (and the ecosystem functions) are sustainable in order to minimise both ongoing maintenance and inspection requirements.

5.7.3 Post-closure Inspection and Monitoring

The size and environmental significance of the MWF will require that the inspection and monitoring system be retained in the immediate period after cessation of disposal operations. As the rehabilitation works near completion, the frequency and intensity of these routines can be reduced but will need to be continued, albeit at a lower intensity. Post closure, there is therefore a requirement for an ongoing programme of monitoring, instrumentation and of inspection, both locally and by a competent independent external expert (Sect. 7.2). The continuation of this programme is consistent with statutory requirements in Europe for long-term inspection of embankment dams and tailings depositories, and it is essential that arrangements for ongoing responsibility and financial provision be put in place to account for this cost (Table 7.10). Finally, the system of inspection may need to extend for a period of years after closure and should only cease once the IIE has signed-off on the facility, declaring that it no longer represents a risk to life or to the environment.

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