STABILISATION OF TAILINGS DEPOSITS: INTERNATIONAL EXPERIENCE

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ABSTRACT: The tailings deposits that remain on the site after mining ceased present a considerable post- mining liability. Environmentally acceptable reclamation solutions for the decommissioned tailings ponds can be achieved by integrating the tailings deposits into the landscape either by turning the tailings pond/deposit into a lake and maintaining a permanent water cover over the deposit or by stabilizing of the deposit into a "dry" landform. Experience shows that risk assessment of the liability can provide the answer to the question which remediation strategy is the best choice for the site.

For remedial preparation and planning the appraisal of the bearing capacity and consolidation behaviour of the tailings is an essential requirement. Particularly in case of soft tailings it is unavoidable to use Non Linear Finite Strain (NLFS) codes. The NLFS program system using the Consol2D code offers numerous advantages for calculation of settlement in inhomogeneous deposits, for 3D quantification of the settlement trough and for evaluation of the drainage effect of the vertical drains. The implementation of the remedial measures is controlled by the shear strength and critical geotechnical parameters of the tailings and vary according to the tailings type and zone. A resistant finale shape and durable final cover are required for creation of a stable landform after reclamation. The important considerations for the long term are revegetation, erosion protection, infiltration control and good surface water runoff.

Introduction: Tailings as a Mining Liability

The tailings deposits that remain on the site after mining has ceased present often the largest post-mining liability. Historically, the quantities of tailings in deposits (and thus the associated liabilities) increased proportionately with the increase of milling capacities. Many of the tailings ponds currently undergoing remediation were designed and constructed using methods and technologies that would be considered inappropriate by today standards. The tailings impoundment designs and construction practice used by mining companies (such as WISMUT) in the past, contain inherent deficiencies that must be remediated today.

The left behind tailings ponds present not only costly remedial and safety problems but also a financial and political risk. From an environmental perspective, the challenge is how to control the contaminants release (such as As, Ra, U, Ni etc.) from tailings and how to prevent the acid generation in tailings containing pyrite or other sulphides. From a geotechnical point of view the biggest challenge is the stabilisation of the very fine tailings (slimes) generated by very fine grinding or by high initial clay content of the ore.

Indeed, already the sheer volumes of the tailings produced is an inherent liability. The tailings production in the mining industry increased from a few 10's of thousands tonnes per day in the 1960's to a few 100's of thousands tonnes per day by 2000. With the increase of the tailings masses the frequency of tailings impoundment failures increased as well. The measure of consequences of a tailings impoundment failure today includes beyond the straight forward clean-up costs the international political damage for the company as well.

The largest tailings impoundments in countries such as Norway, Sweden, Germany, France that discontinued mining seldom contain more than 10's of millions of tons of tailings. The tailings deposits accumulated by the mining companies in US, Canada, Australia and South Africa amount to many 100's of millions of tons of tailings and several will reach billions of tons before closure.
The countries that will have the largest tailings deposits reclamation problems in the future are likely to be the emerging countries like Indonesia (Grasberg mine), Papua New Guinea (Ok Tedi mine), Peru and Argentina and the well known producers in Chile, Brazil and Australia.
Because of the mentioned political and financial risks, the international mining companies and financial institutions started requesting tailings ponds to be developed to "international standards" to limit the potential environmental impacts and unforeseen reclamation costs. The disclosure of the mine closure liabilities is a commonly requested requirement of national financial Security Commissions regulating public companies.
To deal with the issue, Syncrude completed in 1997 a study evaluating the closure and landscaping practice of a number of Canadian and US mines [1].
In follow up two international workshops were organized by Syncrude and WISMUT on "Stabilisation of Fine Tailings": Workshop No. 1 "The scientific basis" took place in Edmonton, Canada, May 26-27, 1999 and Workshop No.2 "Practice and Experience" was held in Chemnitz, Germany, June 23-25, 1999 [2].

Tailings Ponds Design and Risk Optimisation

An important goal followed in tailings management is the minimization of the liability after closure. In technical terms this can be achieved by: (a) stabilisation of the impoundment/deposit, (b) provision of hydrological control, (c) control of seepage, (d) integration of the created land forms (after reclamation) into the landscape, and (e) minimisation of the need for water treatment, surveillance, and monitoring. Beside economics, regulatory requirements have a decisive effect on the extent to which these goals must be met. Commonly, feasible and environmentally acceptable remedial solutions meeting these goals are achieved by stabilisation of the tailings ponds into a "dry" landform [3].

When planning new tailings ponds the single largest design option controlling environmental liability and subsequent reclamation costs is the site selection. The advantages offered by suitable siting has not been adequately used in the past. Surprisingly, even today very large mines, such as the Ok Tedi mine in Papua, New Guinea and the Grasberg mine Iran Jaya were using a direct tailings discharge into the sea. Mine developments like this present today the largest environmental liabilities and are sure to ultimately require very extensive remediation and reclamation.

Countries such as Canada and Norway have abundant natural water bodies (lakes) and sites where water-retaining dams can be created to allow tailings to be placed below lake water surface. In the particular case of tailings containing sulphides, aquatic disposal has the advantage that oxidation of the tailings and associated acid drainage is prevented. A disadvantage of stopping discharges to streams and rivers is the accumulation of tailings and water in dams which, if and when they breach can cause sudden and considerable damage.

A very extensive upgrading of tailings dams, including internal cut-off walls, durable downstream drainage blankets and berms, installation of upgraded diversion and spillway systems has been required to achieve long term control of water levels in the remediated tailings impoundments at Elliott Lake, Ontario Canada.
A combined approach to mine tailings disposal is under development in the Canadian oil sand industry. Syncrude is presently testing combined wet and dry disposal technologies to deal with the fine tailings. By applying a multiple solution to tailings disposal/reclamation using water capping,

composite tailings and thickened tailings a diversified landform can be created which fits into the landscape of Northeastern Alberta [4].

More recently the placement of high sulphide tailings and pyrite concentrates and of soluble contaminants (e.g. Arsenic concentrates) in underground mines has raised concerns about the potential release in the future. At the Golden Giant mine at Yellowknife, Northwest Territories, Canada, for example, requirement for removal of such soluble tailings for alternative disposal has created large remediation liabilities.

In the gold mining areas of Southern Africa (with high evaporation rates and low labour costs) the practice is to hydraulically dispose of tailings into paddies and construct/stabilise the walls by decanting and evaporation of the water from the perimeter paddies. If high rates of rise prevent adequate drying, such embankments are highly susceptible to failure. If the embankments contain acid generating or contaminated material, the protective measures, such as covering, can only partly help control the release of environmentally damaging seepage.

The upstream spigotting of tailings from the tailings dam forms inward sloping beaches on which the tailings segregate depositing the courser sands at the perimeter and concentrating the fine slimes in the pond area. This type of construction is common in the copper mines of southern Arizona, USA, platinum mines in South Africa and at the WISMUT, Germany. The outer embankment is in case of spigotting periodically raised, by building up small perimeter walls using the coarse tailings from the beach and sometimes imported earth. The stability of the dam is provided by the higher (than the slimes in the central parts) permeability of the coarser tailings near the perimeter of the dam. The uncompacted perimeters of these sandy embankments can be susceptible to liquefaction. For long term stability, these dams rely on drawdown of the phreatic surface and therefore a good underdrainage is essential. If a high water table is allowed to develop in the perimeter of such dams, the risk of dam failure becomes a serious issue. A number of tailings dams of this construction failed in Chile in the early 1960's. The long term reclamation of this type of dams usually requires a costly construction of stabilising berms.

Tailings conditioning by mixing tailings types of different geotechnical properties, or adding additives to tailor geotechnical properties is being intensively evaluated at Syncrude and Suncore in Alberta, Canada [5]. By providing an appropriate mix, the tailings segregation and drainage characteristics can be tailored to provide in a deposit with more uniform and desirable properties, which are more readily remediated on impoundment closure.
Lastly, there is increasing use of geochemical conditioning to render tailings, or a proportion of the tailings less contaminant generating. The segregation of most of the sulphide minerals from an acid generating tailings is proposed for some new mines, including the Pogo mine in Alaska.

Lately, risk management approaches were introduced for assessment of tailings liabilities. The use of the approach is mainly due to increased requirements for good corporate governance at mining companies and due to the oversight requirements of the institutions responsible for funding of the mining or remediation projects.

The costs and risks of the wet and dry rehabilitation options and associated strategies were compared in detail (paying special attention to dam safety) using a probabilistic approach at WISMUT [6]. In densely populated areas (such as in Saxony with 247 inhabitants per km² and in Thuringia with 154 inhabitants per km²), a 100% level of the probable equivalent costs (sum of the reclamation costs and environmental gains/costs) was considered necessary. Under these assumptions the dry landscape reclamation offered a better long term performance. However, the equivalent reclamation costs for the wet option remained up to the 65% probability level lower than for the dry option, thus presenting an efficient solution for the less populated remote areas (Fig.1). The better cost efficiency of the dry reclamation at the 100% level is due to lower susceptibility to deterioration and disruptive events thus resulting in lower costs for damages, repairs and clean-ups in the long term.

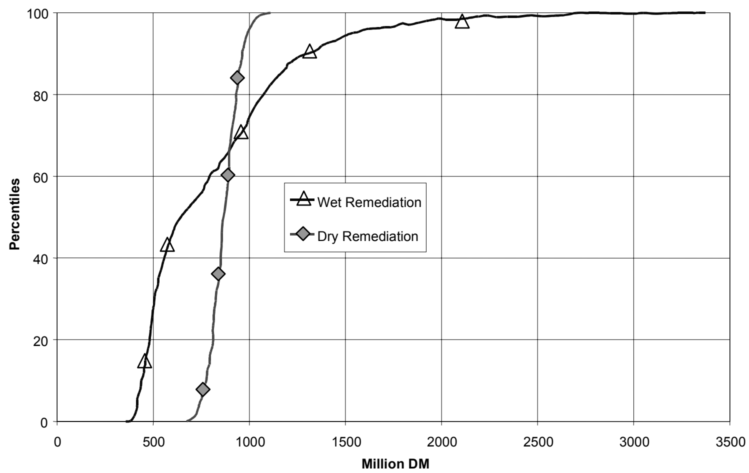


Fig. 1 Equivalent Costs for the Wet and Dry Tailings Reclamation of the Helmsdorf pond.

Remedial Preparation and Measures

During remedial preparation and planning, the laboratory and field measurements of material parameters are collected, evaluated and integrated [7]. Data and information describing the pre-constructional topography, embankment details, material balance, unexpected occurrences are collected and analysed. In addition to material characteristics, the thickness of the deposit, the tailings discharge/deposition history, and the drainage conditions at the tailings pond base are evaluated. Aerial photographs proved to be useful for confirmation of the location of the tailings discharge points.

The zoning of the tailings deposit into sandy, intermediate and slime zones is based on in situ vane shear strength measurements combined with physical sampling and estimation of the geotechnical properties (such as grain-size distribution and moisture content measurements, solids specific-gravity determinations, Atterberg limits, and laboratory shear strength). To capture the behavior of the fine tailings during the early stages of consolidation (at very high water contents) both Syncrude and Wismut use specially built large diameter oedometers.

The basic composition of the Clark Hot Water Extraction fine tailings at Syncrude is sand, silt and clay with traces of bitumen. Although the milling and grinding of the ore at Wismut produced fine rock flour, the fine tailings contain clay minerals as well. To avoid the possibility of unexpected liquefaction due to thixotropic behaviour, the sensitivity of the tailings is preventively checked while considering the differences due to grain size distribution, mineralogy and chemistry of the deposits. This is done by testing the time dependent change of the torevane strength, combined with data on the sensitivity of the tailings defined as the ratio of the intact to remoulded vane shear strength.

Access onto the soft slimes zone of the pond for purposes of cover placement is increasingly problematic for the more recently developed tailings dams constructed at high rates of rise. In such impoundments the fine slimes are often highly underconsolidated with high excess pore water pressures and very low shear strengths. Natural processes of consolidation may take tens of years before pore pressures dissipate and settlement ceases. Reclamation profiles must either allow for such long term consolidation or the process must be accelerated. To this end increasing use is made of band drain. They are installed the full length of the tailings to accelerate consolidation of the entire tailings mass or only in the upper few meters to allow surface consolidation to the extent that access onto surface can be achieved for cover placement.

For planning remedial measures, two basic questions are of importance:

(1) Is the bearing capacity of the tailings surface sufficient for machinery and material to advance the cover, and

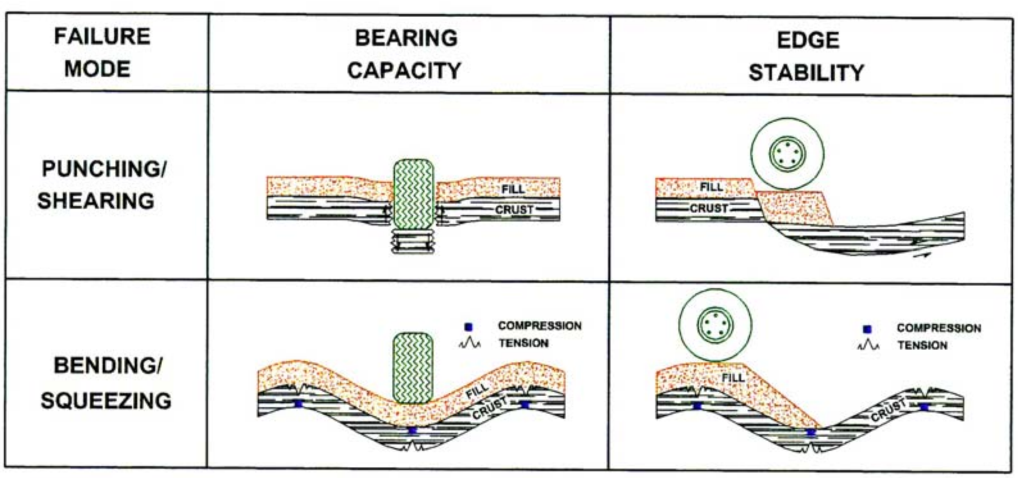
(2) How large is the rate and amount of settlement of the tailings surface induced by the load of the cover.

Bearing Capacity

Beyond static load, the evaluation of bearing capacity must consider the effect of machine loading during soft tailings stabilisation (dynamic loading) as well as the three-dimensional nature of the loading geometry. Neither of these effects is simple to account for. And, because the cover layer is often unsaturated and at low stress, apparent cohesion (suctions) and high friction angles (under low stresses) are common yet not considered in the analysis. Besides the problems associated with an adequate description of the failure mechanism, the mathematical evaluation is complicated by the presence of a crust or thin cover layer on the soft tailings.
The practice followed during covering is to use a conservative analysis and bound the issue into safe limits.

The failure modes of tailings surface bearing capacity as summarized by Syncrude are presented in figure 2.

Figure 2 Bearing Capacity Failure Modes of Tailings Deposits (after Syncrude)



Settlement

The settlement (change of surface elevation over initial thickness) observed for soft tailings due to self-weight consolidation is commonly in the order of 30 %.
For settlement modelling the collected data are evaluated to provide the following material functions: (1) Void ratio – effective stress relationship, (2) deformation modulus E and (3) Hydraulic conductivity – void ratio relationship [8].
The settlement of classical, homogenous, soil-like tailings can be predicted by the consolidation theory of Terzaghi. For calculation of the soft tailings settlement which depends on the pore water content, under a time dependent load, finite strain models (NLFS) are required. A 1-dimensional

NLFS code, ACCUMV, was developed for this purpose by Schiffman and his associates [9]. An other 1-dimensional NLFS code, FSConsol, [10] extended the use of the Schiffman code to allow the assessment of the tailings self-consolidation during the discharge phase. A comparison of four different NLFS codes showed no substantial differences for the case of a well defined borehole profile in the WISMUT tailings pond at Helmsdorf [8].
Unlike other NLFS codes, Consol2D (developed at WISMUT), is based on a 3-dimensional approach with the calculations reduced to a 2-dimensional problem. The modelling framework can handle radial-symmetric (for vertical drains) and two dimensional (for evaluation of the effects of horizontal drainage) problems. The settlement can be modelled for layered tailings having up to 10 different material types. Measured or calculated void ratio depth profiles are used as initial conditions. Pore pressure distributions can be defined as boundary conditions [11]. The model was validated and verified with in situ measurements involving the use of vertical drains [12].
The quantification of the settlement volume is required for planning the amount of fill material required and the seepage water treatment plant capacity. For example, in case of the Wismut tailings ponds it was concluded that a 2 m thick cover would result in a settlement volume in the order of approximately 3 million m^3 and the release (surface and basal) of approximately 300 000 m^3 of pore water.

Remedial Measures

Numerous techniques have been developed to allow access onto the surface of weak unconsolidated tailings. The most widely used approach is to allow drying to form a “crust” of desiccation strengthened tailings, reinforce this with synthetic geogrid, and then advance thin layers of cover fill using light equipement. An example of extensive covers placed by such techniques is the covering of the WISMUT tailings ponds in Germany.

The “dry” tailings reclamation strategy followed at WISMUT involves the following steps:

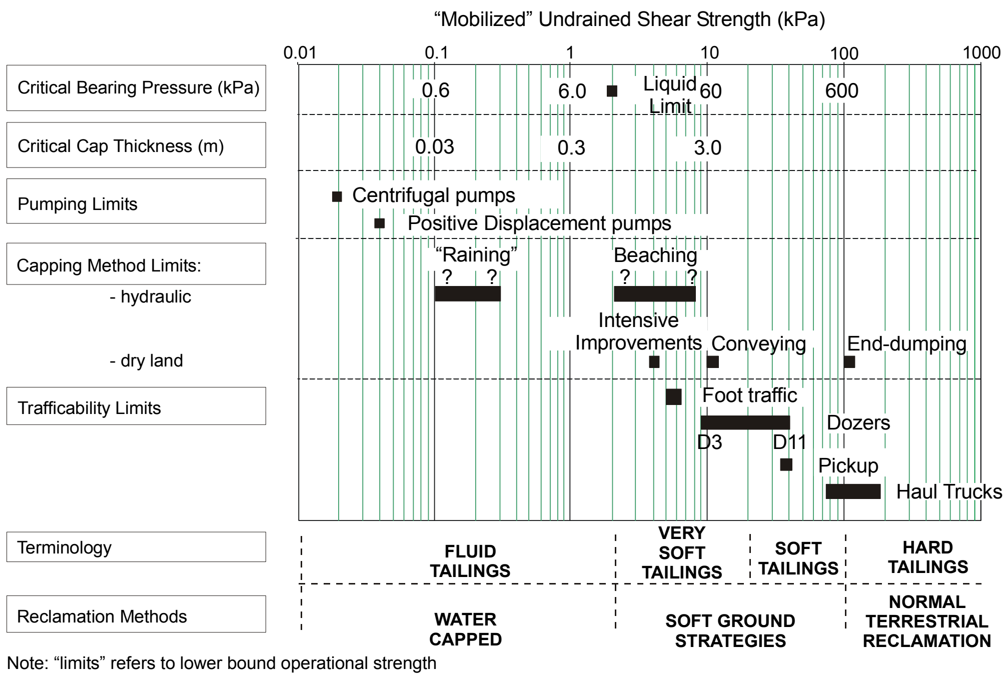
(1) Decanting of the “free” pond water
(2) Placement of an interim cover on the tailings surface to provide the consolidation load an create a stable working platform;
(3) Building of a stable surface contour providing suitable run off conditions for the surface water;
(4) Capping of the surface with a final cover.

Each remedial step leads to a disturbance of the geomechanical balance which then has to be allowed to re-establish before taking the next step. The general direction of remediation is from the sandy beach zones toward the slimy central parts of the impoundment. The performance of dry cover placement on tailings with a shear strength above 5kPa is described in detail in [3].

Advancing over slimes of lower shear strengths (< 5 kPa) requires thinner initial cover layers and use of lighter equipment and/or use of a long arm hydraulic shovels [7]. A subaquatic placement of the initial cover layer onto slimes is used at the Helmsdorf site of WISMUT. The approach is rather complex but has the advantage that the total weight of the initial layer can be applied to the slimes in small increments with no construction equipment load.

Various techniques for promoting surface drainage (trenching using amphibious equipment) and air drying (including vegetation enhancement of drying, transpiration) have been used. Sand cover placement with hydraulic means has also been successfully used at the Syncrude tailings facilities in Alberta, Canada. The remediation methods used for various tailings types/zones (as summarized for Syncrude) are presented in figure 3.

Figure 3. Remediation methods as a function of tailings shear strength and critical parameters.



A very important part of the construction of the interim cover is the vigilant observation of the tailings response to cover placement and the flexible adjustment of the advancement and technology to the changing field conditions and changing material properties.

Final Cover

Final covers are installed with the objective to (1) provide a medium for revegetation of the surface, (2) control erosion, (3) separate surface flow from contacting the tailings, and (4) reduce infiltration [3].

Erosion control is usually achieved –pending on the climate- by vegetation or coarse gravel cover.

For infiltration control either barrier covers can be used which limit infiltration by incorporating a low permeability layer or evaporative covers which maximize infiltration storage in the cover until such time till it can be removed by evapotranspiration.

Experience shows that barrier covers are highly susceptible to disruptions arising from differential settlement, cracking, root penetration, burrowing animals and human actions.

The functionality of an evaporative cover depends very much on the local climatic conditions. The advantage of the evaporative covers –if feasible for the site- is the high durability and lower costs.

The cover thickness vs. field capacity ratio of the final cover is best selected such to achieve a self-sustaining soil water balance under the local climatic conditions, i.e. a balance between infiltration and evapotranspiration. In case of a well balanced cover, the lateral drainage and breakthrough of the soil water can be limited to cases when high precipitations occur repeatedly. An optimised soil cover can be designed by using any reliable soil water balance or soil water movement model, such as HELP or Soil Cover.

For timing of placement of the final cover on soft tailings it must be considered that (a) the compaction of an infiltration barrier with heavy equipment can only be carried out when the consolidation of the soft tailings reached a shear strength capable of accommodating the deformations induced by compaction without cracking; (b) if the consolidation is still ongoing, the cover must be sufficiently flexible to tolerate the differential settlements; (c) the construction must not damage the functionality of the drainage layer; (d) the ultimate surface drainage must not lead to ponding of the surface water; and (e) the long-term settlement must not alter the slope of the drainage patterns on the cover surface and within the cover.
Ideally, the consolidation should have reached approximately 90 to 95 % of the total settlement before placement of the final cover.

Covers are particularly sensitive to erosion on moderately to steeply dipping slopes (5 to 30% slopes), which are common for tailings embankments. To reduce the potential for development of rills and gullies it is a good practice to break long slopes by building drainage berms at intervals of 25 to 50 m. Slope drainage is collected on the berms in erosion resistant ditches, which conduct drainage down the berm and off the embankment. Regular cleaning of accumulated sediments and vegetation from the ditches must be planned to maintain functionality.

Concerning cover failures, surface slumping is the most common mechanism in Northern Canada, where winter freeze is deep and perched water tables develop in frozen layers in spring. Under moderate climatic conditions, the drainage capability in the surficial layers is the most important factor controlling failure.
Although, dam slopes for long term can only be designed on a site specific basis, slopes of 3H:1V proved to be demonstrably stable under most of the conditions. In order to keep the drainage channels on the dams functional, the slopes should, however, never be flatter than 3V:1H under any climatic conditions.

The final shape of the remediated tailings pond usually follows either (a) a dome shape over the slimes pond which drains toward the embankment, or (b) a valley shape sloping toward the pond centre and discharging through a channel from the pond to a spillway on the embankment. The doming shape is most commonly used on well draining tailings deposits at places where abundant earth material (or equivalent) is available at low costs. For the present day tailings ponds it is more efficient to plan a valley shape contour requiring less earthen material to be imported.

Conclusions

Although there is a number of different methods for construction and operation of tailings ponds, the problems associated with reclamation tend to be similar. Tailings have a very fine grain size and complete dewatering is very difficult under most climatic conditions. In some situations mining companies opted to store saturated tailings in a permanent pond on the surface, which means that the stability of the impoundment became imperative, even after the site has been reclaimed. The "dry" rehabilitation is, however, the preferable long term option in densely populated areas.
All tailings impoundments leak, even if lined, and the amount and nature of the seepage dictates the method of reclamation. The single largest post mining burden is the long term operation and maintenance of seepage intercepts and water treatment systems. These requirements have driven recent bonding and closure fund financial assurance provisions.

Tailings ponds reclamation should be aimed toward a clearly defined future land use, whether active or passive for the area. The land use should be determined in consultation with local communities and the government. Successful reclamation to a low maintenance land use, which is sustainable in the long term, requires an understanding of land forms, soil development and plant succession. The main aims of reclamation are to reduce the risk of pollution, to restore the land and landscape and to prevent further degradation so that the resulting conditions pose minimal risk to people and the environment both in the short and long run. In response to this upgrading it is reasonable to expect that the value of the reclaimed land would increase and the mine operator will be able to transfer the site without future liabilities.

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